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ESCOLA D'ARQUITECTURA DE BARCELONA
ESCOLA D'ARQUITECTURA DEL VALLÈS

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STRUCTURAL CARDBOARD

FEASIBILITY STUDY OF CARDBOARD AS A LONG-TERM STRUCTURAL MATERIAL IN ARCHITECTURE

PROJECTE PRESENTAT PER
Branko Sekulić

TUTORS DEL PROJECTE
David Garcia i Carrera
Jordi Payola i Lahoz

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Structural cardboard

Feasibility study of cardboard as a long-term structural material in architecture

Cartón estructural

Estudio de la viabilidad del cartón como material estructural de larga duración en arquitectura

Branko Sekulić

MÀSTER UNIVERSITARI EN TECNOLOGIA A L'ARQUITECTURA
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TRIBUNAL:

Jordi Maristany
Robert Brufau
Joan Ramon Blasco

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Abstract

This study aims to evaluate the feasibility of cardboard as a long-term structural material in architecture. Recent experiments with cardboard in architecture are based on assemble of structural elements with existing cardboard products, which are afterwards put to load tests. Obtained results are usually in lack of coherence, making difficult to have precise prediction of structural behavior on a long-term basis. On the other hand, information that comes from packaging industry does not respond to architectural needs of material, so architects face difficulties toward closer understanding of mechanical properties of cardboard.

The approach in this study goes from inside to outside, trying to understand the properties of the smallest components of the material and its relation with surrounding. Analyzing the microstructure in this direction helps to see which is the most convenient way to intervene for obtention of the optimal carton-based material for structural use in architecture. *(Keywords: Structural cardboard, Pre-stressed paper-cement, Recycled cardboard structure, Cellulose fiber composites, Efficient cardboard structure)*

Abstract

El siguiente estudio trata de evaluar la viabilidad del cartón como material estructural de larga duración en arquitectura. Recientes experimentos con cartón en arquitectura se basan en ensamblaje de elementos estructurales con productos existentes de cartón, los cuales son posteriormente sometidos a las pruebas de carga. Los resultados obtenidos generalmente carecen de coherencia, así que es difícil predecir con precisión el comportamiento estructural de larga duración. A su vez, la información que proviene de la industria de embalaje no responde a las necesidades arquitectónicas del material, así que los arquitectos encuentran dificultades hacia la comprensión mas cercana de las propiedades mecánicas del cartón.

El enfoque en este estudio va desde dentro hacia fuera, intentando comprender las propiedades de los componentes mas pequeños del material y su relación con el entorno. Analizando la microestructura de esta manera ayuda a ver cual es la manera mas conveniente para intervenir, con el objetivo de obtener un material óptimo a base de cartón para usos estructurales en arquitectura. (Palabras clave: Cartón estructural, Papel-cemento pretensado, Estructura cartón reciclado, Compuestos fibras celulosa, Estructuras eficientes cartón)

Index

Part 2

Part 3

1. Introduction

1.1 **Background**

This study is a continuation of my colleague's work Maria Isabel Umbert [45], as a part of research line at Polythecnic University of Catalonia (UPC), where she faced problems with numerical characterization of cardboard when designing a prefabricated structural element of this material.

Demand for environmentally friendly materials increased as a consequence of our environmental awareness, therefore, reutilization of cardboard in architecture is very interesting option. Production of pulp and large-volume paper products such as newspapers and magazines are starting to stagnate. Small improvements in existing products cannot significantly increase the demand. The greatest issue is to find new concepts which could increase the capital value of wood fibers, while competing with other natural fiber-based materials.

According to the FEFCO [50], "*(...) around 90 percent of consumer products are shipped in cardboard which makes it the largest component of waste in municipal dumps and one of the most important items to recycle.*"

In architecture we can find many experiments with this material, but almost none has responded as a durable load-bearing structure. Interesting properties of cardboard as strength-to-weight, economy and accessibility, followed by successful projects of architect Shigeru Ban, have motivated in recent years many architects to research in the field.

The most frequent problems architects face are the evident vulnerability of cardboard in exterior conditions, but also the lack of reliable and consistent mechanical properties data for architectural structural design. Consequence of these problems are two main streams that architects have adopted. One is the search and comparison of outcome from diverse experiments in order to find the (lower) average number which could be useful and reliable for calculation (e.g. study of Maria Isabel Umbert [45]). The second one is empiric approach where architects design and assemble structural elements using existing cardboard products, putting them to load tests and obtaining results afterwards. Frequently, both of these approaches lead to incoherent results which are followed by certain unconsciousness about the internal laws which rule cardboard's microstructure.

Although the aim of this work is not to analyze architectural projects made of cardboard, it is in interest to explore this material and understand its micro structural laws and the reason of its short life as a structure.

1.2 **Objectives**

The main interest of this work is to help architects to explore, get closer and understand the microstructural mechanisms of cardboard. Unlike empirical approaches previously mentioned, the intention of this work is to try to scope a range of numerical data for structural design in architecture through a theoretical approximation.

Microstructural insight is an essential step before we decide which interventions cardboard may or may not need in order to convert it in a durable load-bearing structure and before we start to assemble elements and put them to load tests.

Therefore, two main objectives are established in this work. The first one is the characterization of material for structural use in architecture, and the second, indications for improvement of its properties as a durable load-bearing element. Without claiming to be ambitious, this study is intended to serve as a basis for future development of cardboard based durable load-bearing structural elements.

1.3 **Methodology**

The system of methods in this work consists in compilation of scientific researches from diverse fields related to cardboard (reviews, publications, dissertations, phd studies, etc.) as a fundamental background, but always keeping the focus on structural use of cardboard in architecture. The first approach discards all the information which is no relevant from this point of view. In the beginning, the scope is completely opened, starting to narrow as the research proceeds.

Once the scope becomes specifically narrow, material characterization is approached. It is based on compilation of data, tables, graphics and useful informations from relevant researches and experiments, which are studied and compared in this work, leading finally to numerical orientation of mechanical properties of cardboard.

The key method is a understanding of microstructural mechanisms, which is based on scientific researches from paper industry and university departments worldwide dedicated to the subject. Once related all relevant information with microstructural mechanisms, begins the final part of this research, which is theoretical characterization of structural cardboard. It consists in detection of necessary material improvements for structural use in architecture, analysis of the intervention strategy, and finally, mechanical properties expectation of structural cardboard.

1.4 **Research structure**

This study is divided in three parts, each one consisting of two chapters. Every chapter contains some important observations in a way of semi-conclusions, which are highlighted for easier detection. Each of the first two parts is finished by a summary which indicates the more specific scope of the next part. The study is completed with conclusions and recommendations, which represents the summary of the third part. First two parts are relied on the most relevant scientific sources from reference list, while the third part tries to adapt microstructural cardboard mechanisms for architectural needs, based on theoretic study of previous parts.

The first part is an essential approximation to the subject. It begins with historical overview of cardboard's use in architecture, after which the scope is focused to the cardboard itself as material. The aim is to disintegrate it into smallest particles, understand their properties and afterwards, zoom out again summarizing cardboard's basic properties.

The second part follows the indications from the summary of the preceding part, directing the study to the Kraft paper mechanical properties. First chapter of this part analyses important factors which influence mechanical properties of paper products. Next chapter focuses on long-term mechanical properties, concluding with approximate values of linerboard.

Indications from the second part open new point of view, which is explored in the third part. In order to improve some weaknesses of cardboard for structural use in architecture, the first chapter of this part studies intervention strategy and its theoretical effects, while the final chapter tries to evaluate mechanical potential of the structural cardboard.

The research structure follows the evolution of the research process, as mentioned in methodology, starting from very wide scope, narrowing the point of view into specific area.

Part 1

2. Historical overview

2.1 **A brief timeline usage of paper and cardboard**

The first cultures to use paper as a building material were Chinese and Ancient Egyptian. In the beginning it was used in form of *papier màché*, followed by development of papyrus by the 2nd century B.C. By the 9th century A.D., Japanese culture started to use paper elements in the construction of sliding doors and walls, called shoji-fusuma. That was the first time paper was utilized as an interior building component. France was the first to use paper in furniture production in 19th century, and later as wall covering, introducing for the first time in history paper as a decorative function.

Corrugated paper was used for the first time in 1856 for hat production, by two British entrepreneurs. Later on, they obtained a patent for a similar technology used in the packaging of fragile items. Introduction of the first continuous corrugation machine in 1895 followed those new uses.

Paper products were being used in the production of aircraft and tank components in World War I. When discovered that aluminum had problems with expansion and shrinking, the substitute for aluminum sheeting on aircraft wings came in form of plaster-made mold for shaping and cellulose reinforced sheets of paper combined with starch or similar adhesives.

By 1920's, paper and cardboard started to be used as electrical insulation in the United States. In the same period impregnation experiments began with introduction of cellulose fiber laminates into the industry. First, phenolic-resin was used, until development of melamine resins led to the increased popularity of paper and cardboard as a building material.

In following decades, several architects began to experiment with paper as a structural material. Some of the most interesting works will be overviewed in the following section 2.2.

As we can notice, paper products are becoming very popular in academic researches.

"Today, research into the pulp, paper and corrugated cardboard fields has evolved extensively, and is now represented by worldwide trade associations such as the European Federation of Corrugated Cardboard Manufacturers (FEFCO). Additionally, basic materials research and development into pulp and paper products is being pursued at several academic institutions, some of which now devote entire departments to the field, such as Georgia Institute of Technology's (USA) Institute of Paper Science and Technology and Helsinki University of Technology's Department of Forest Products Technology, Paper and Pulping Technology." [06]

2.2 **Use of cardboard as structure in architecture**

The first building constructed principally out of cardboard was *The 1944 House*, followed by a period of slow development in the field. Several architects have influenced the progress of use of cardboard in architecture, with the two most influential figures, Buckminster Fuller in 1950's, and Japanese architect Shigeru Ban, most recently.

"*Fuller, with his innovative vision and experimental application of cardboard components in architecture, has been highly influential in providing the framework for this field of study. He was the first designer who seriously contemplated and worked with cardboard as a building material. His approach was based on a philosophy that combined environmentally sustainable building concepts with economically sustainable financial terms*." [06]

In the decade following Fuller's groundbreaking work, a small number of architects and engineers continued to experiment with cardboard as a building material.

Generally, the developmental history of cardboard building projects is divided into three periods:

1. The birth of cardboard building prototypes (from 1944 through the early 1990's).
2. The Shigeru Ban cardboard works.
3. The development of contemporary prototypes and approaches during the last decade

In mentioned examples, cardboard was used because of its low cost, ability to be mass manufactured, and its minimal environmental impact. It served structurally either as a primary element or secondary supporting element. Mostly, geodesic domes and other polyhedral macro forms of cardboard were developed and tested as and answer to the main problems cardboard provoked. It was necessary to maintain the structural strength and stiffness when confronted with eternal weather conditions, humidity and fire, and these architectural-structural solutions were determined to be the most efficient solution.

The most common method used for weatherproofing and sealing these early cardboard building prototypes was the application of substances such as boiled linseed oil, copal varnish, polyurethane paints, resin-based paints, fiberglass and concrete on the outer surface of the structure.

Cardboard proved its structural potential and offered high degree of flexibility in construction, demolition and disposal. However, these significant roles cardboard offered have not been thoroughly pursued beyond the prototype level. Those initial applications failed to fully utilize building potential of cardboard and were mostly ephemeral in nature.

(...) *The majority of the early prototypes failed testing beyond short-term, small-scale applications. The implementation process into the mass development of cardboard as a commercially-feasible and socially-accepted building element proved to be in need of further development and testing.*"[06]

With changing technology and apparition of new plastic-based materials in postwar period, started a period of relative disinterest and slow development of cardboard as a building material. In the mid 1990's, Japanese architect Shigeru Ban started to use paper tubes as a structural elements in architectural design. Today, after nearly twenty years of long-term testing, these projects have demonstrated the potential of paper products as a viable building material. Aspects as relatively low cost, high recyclability, low environmental impact and structural strength and stiffness, led to the global success of his projects and re-energized the field.

Until now, the most significant example of a modern cardboard application is the Westborough Primary School in Westcliff-on-Sea, England, designed by architects Cotterel & Vermeulen in 2001, Fig. [II / 2]. The Westborough School progressed beyond the prototype level, and is foreseen to have an extended lifespan, although, its principal structure is wooden truss. Another such attempt was The Cardboard House, designed by architects Stutchbury & Pape in 2004, in association with the Ian Buchan Fell Housing Research Unit at University of Sydney, Fig. [II / 1] (i). Also in 2004, Adriano Pupilli of the University of Sydney, in cooperation with the firm Armacel, constructed a cardboard structure using a composite material.

In academic field, cardboard building research has also found an increased interest. Actually, Institutes such as ETH-Zurich, The Architectural Association in the United Kingdom, and TU Delft in the Netherlands conduct experimental and theoretical research into cardboard as a feasible building material.

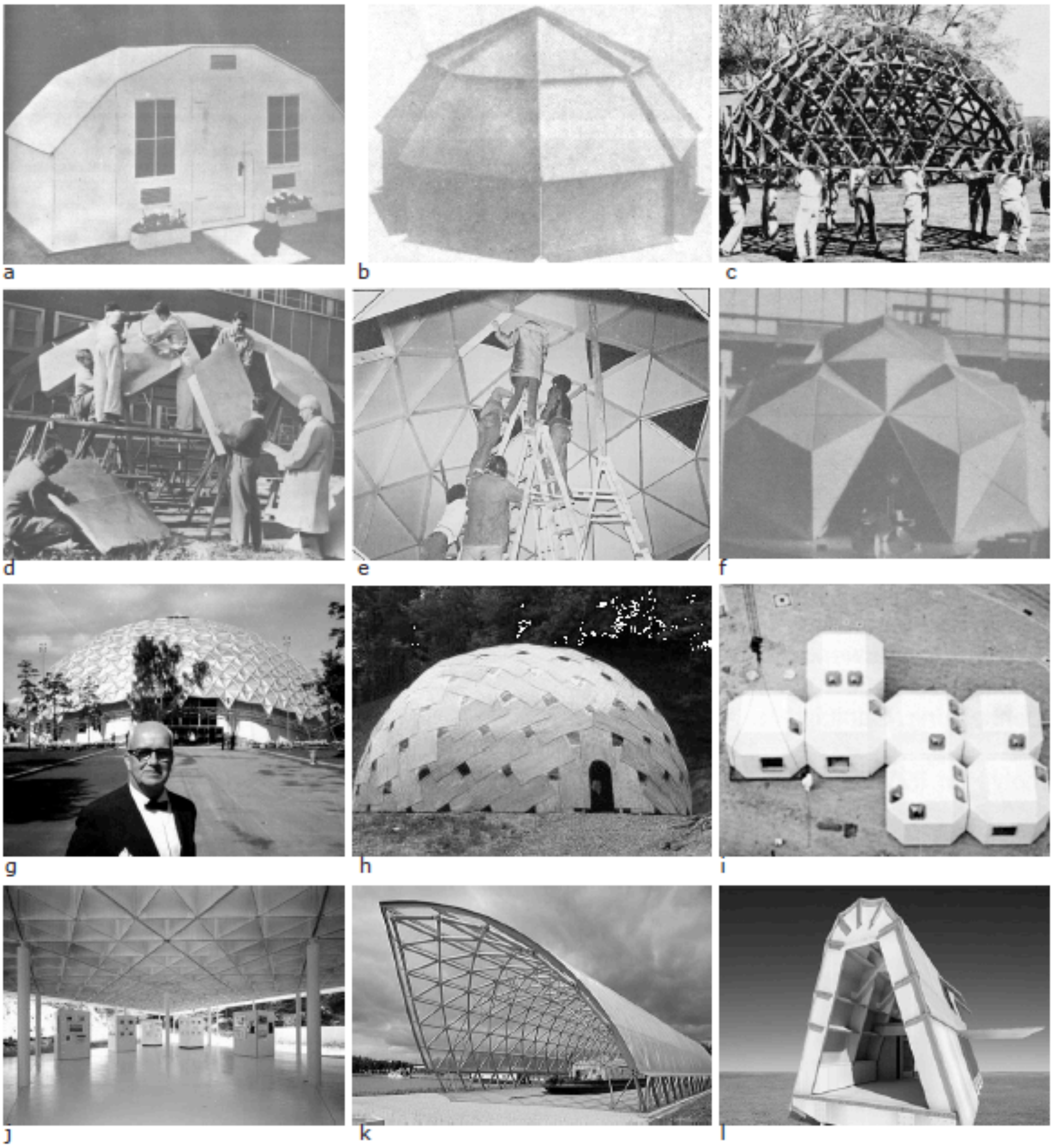


Fig. [II / 1] - (a) 1944 House; (b) Emergency Shelter, by Container Corporation of America (1954); (c) Paperboard, geodesic dome, coated with polyester resin, by Buckminster Fuller (Tulane University, 1954); (d) Paper Dome (McGill University, 1957); (e) Charas Project, assisted by Michael Ben Eli (New York City, 1970) (f) Dome Stéréometrique, by D.G.Emmerich & Jungmann (Exposition of Wegwerf -Architecture, Paris, 1970); (g) Photograph of Buckminster Fuller in front of geodesic dome constructed as the U.S. pavilion at the American Exchange Exhibit, Moscow (1959); (h) The New Generation Plydome, by S. Miller (1994); (i) Casa-Nova Project, by 3 H Architects (Olympic Games Munich, 1972); (j) Nemunoki Children's Art Museum, by Shiegeru Ban (Shizuoka, 1999); (k) Centre d'interpretation du Canal Bourgogne, by Shigeru Ban (Pouilly-en-Auxois, 2005); (l) The Cardboard House, by Architects Stutchburry & Pape (Sydney, 2004). [06]

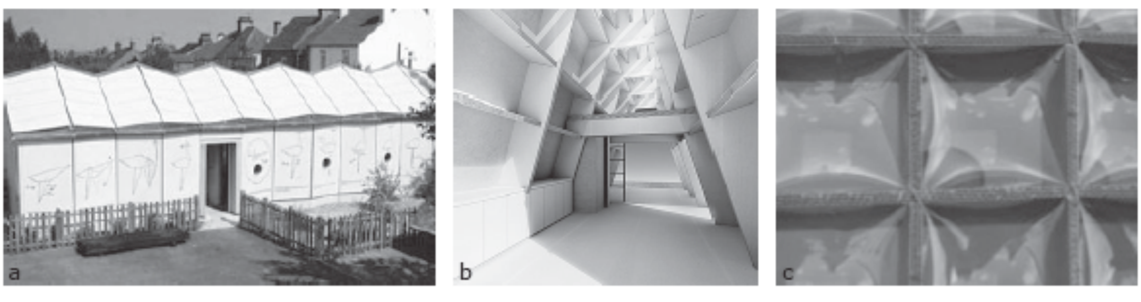


Fig. [II / 2] - Cardboard building study examples1 1 (a) Westborough Primary School (United Kingdom); (b) The Cardboard House, by Stutchburry & Pape; (c) Deflated Facades (TU Delft). [06]

2.3 **State of art**

Despite very extensive research that paper industry achieved in the field of pulp and paper product's production and properties, architects still do not feel totally comfortable using this material. It fulfills all needs for the packaging industry, whose products have mainly short-term character, but lacks precise information and experience in durable load bearing states, specially in external weather conditions.

Therefore, in order to obtain some helpful results for predictions, architects mainly assemble structural elements with existing cardboard products, put them to load tests, obtain certain results and afterwards look for the optimal way to protect these elements.

The main problem faced are incoherent results obtained from different sources, which put even more doubt about properties of cardboard and its long-term behavior. As a consequence, architects try to find an average result obtained from several tests and reduce admissible mechanical properties notably as a safety factor.

This approach leaves certain unanswered questions about potential of this material and mechanical capacity, which could be resolved in a fundamental research, or at least, understood why these incoherencies are happening.

Fundamental research from architectural point of view is the main approach in this study, aiming to understand micro mechanisms of cardboard and find the optimal intervention tools, which could stabilize its properties in durable long-bearing state.

Fig. [II / 3] - Experiments with cardboard in architecture.

3. Cardboard

3.1 **Terminology**

In common language, the term cardboard is mainly associated to material used in packaging industry, either in a form of a “thick paper” or as a sandwich of uncorrugated and corrugated layers.

In business and industry, between material producers, container manufacturers, packaging engineers and standard organizations, the terminology has to be more specific. It is interesting to notice that the term “cardboard” is often avoided because it does not define any particular material.

The paper industry is an excellent source of definitions, although, there is no unique definition for each term. In order to obtain suitable terminology for this research, several sources have been compared and contrasted to finally choose the clearest definitions [53, 54, 31, 55, 43, 36, 02, 41].

Pulp

All plant material basically consist of cellulose fiber, hemicellulose and lignin, which bind cellulose fibers together. Pulping is nothing but breaking/removing lignin to separate fibers. Lignin is physically and chemically weaker than cellulose fiber. Hence when a physical force or chemical is applied to plant (wood, grass, straw, rag...), lignin breaks down faster than cellulose. Heat also weaken lignin faster than cellulose fiber. So pulping processes varies from complete mechanical to complete chemical and any combination in between. [55]

Pulp is a chemically or mechanically produced raw material used in the production of paper and paperboard. It is one of the most abundant raw materials worldwide. Wood provides about 90% of the basis for pulp production.

Lignin

A complex constituent of the wood that cement the cellulose fibers together. Lignin is brown in color. Lignin is largely responsible for the strength and rigidity of plants, but its presence in paper is believed to contribute to chemical degradation. To a large extent, lignin can be removed during manufacturing.

Hemicellulose

A constituent of woods that is, like cellulose, a polysaccharide, but less complex and easily hydrolysable.

Cellulose Fiber

The slender, thread-like cellulose structures that form a sheet of paper. Fibers used in papermaking come primarily from wood and recovered paper. Cotton is also used to make certain products.

Paper

A homogeneous sheet formed by irregularly interviewing cellulose fibers. Paper is used for writing, printing, wrapping, packaging, decorating, wiping etc.

Furnish

A mixture of fibers, water, chemicals, and pigments. The furnish used to make paper has about 1% solid material and 99% water.

Paper board

A heavy weight, thick, rigid and single or multi-layer sheet. What differentiates paperboard from paper is the weight of the sheet. If paperboard is very heavy it is called Board. Paper heavier than 150 gram per meter square are normally called Paperboard and paperboard heavier than 500 gram per meter square are called board.

Paperboard or chipboard is mainly a single layer. Many foods such as crackers, cookies, cereal, pizza, come in paperboard boxes. Carton board usually has three or more furnish layers.

Carton board

Carton board is the common name for paper used in packaging cartons. The material consists of three or more furnish layers manufactured simultaneously on a multilayer paperboard machine (see, e.g. Fg. [III / 1]). Cardboard may be coated with polymers to achieve a material that can be used in ovens, microwaves, and other demanding conditions, or it may be laminated with metal films to enhance appearance and protect the content.

A rigid wood fibre based packaging material. Carton-board is normally of at least 180 g/m2 substance and 250 microns thickness.

Corrugated board

Corrugated board is a sandwich construction with a web core and face sheets made from paper. Container board is the common name for the paper materials used to manufacture corrugated board, and includes liner board, used for the facings, and fluting, which is the paper used in the core. The face sheets and core are typically glued together with a starch-based adhesive. The main function of the core is to separate the face sheets in order to achieve a structure with high bending stiffness. The core must also provide shear transfer between the face sheets to minimize sliding deformation during bending.

Container board

The paperboard components (liner board, corrugating material and chipboard) used to manufacture corrugated and solid board. The raw materials used to make container board may be virgin cellulose fiber, recycled fiber or a combination of both.

Liner board

The inner and outer layers of paper that form the wall of a corrugated board.

Fluting

The rippled middle layer in corrugated board, produced generally from recycled fiber.

Chipboard

A paperboard, thicker than cardboard, used for backing sheets on padded writing paper, partitions within boxes, shoeboxes, etc.

An inexpensive and thick one-ply cardboard usually produced from waste paper. It is used for packaging purposes as well as a backing board for notepads etc.

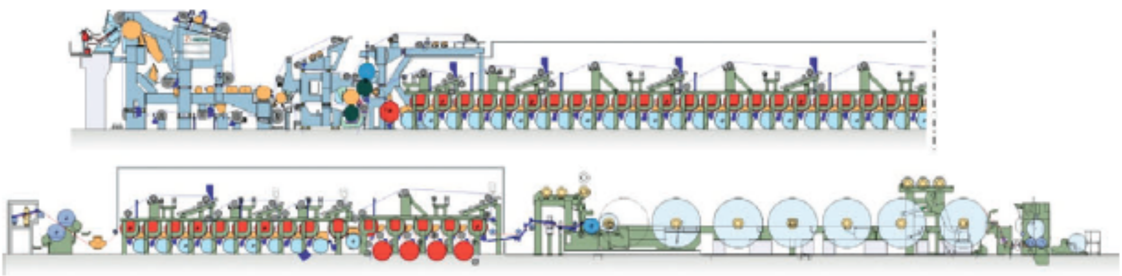


Fig. [III / 1] - Containerboard machine equipped with a gap former and two-layer headbox; courtesy of Metso Paper Inc. [31]

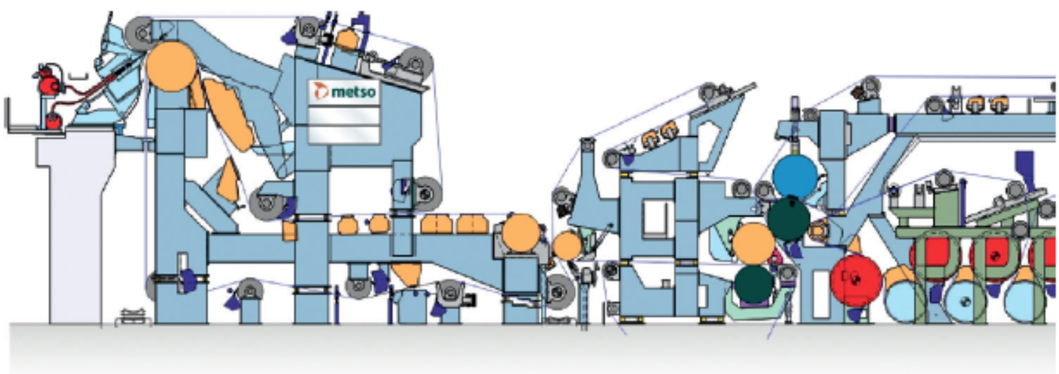


Fig. [III / 2] - Details of the forming section of the machine in Figure [III / 1]. [31]

Observation 1

The base of all paper products is the furnish, a mixture of cellulose fibers, water, chemicals and pigments. Properties of any type of board, solid or corrugated, one- or multi-layered, will depend on properties of furnish components.

The chemicals and pigments are optional components which can improve some properties of the final product. The essential base components are cellulose fibers and water. Therefore the main interest is in study of cellulose fibers.

Cellulose virgin fibers used in production of paper products come primarily from wood. Many different species provide different types of cellulose fibers, which can result in different properties of final paper products. Therefore, to understand those differences, the study of the wood structure is very useful.

In the following paragraphs, the synthesis was made from paper industry scientific researches, with a focus from the outside towards inside, disintegrating wood from its macrostructure to its micro- and ultra-structure, in order to understand the properties of its cellulose molecules.

Once the properties of the molecules are understood, the focus direction is reverse, starting from the molecule towards outside, until the structure of the plant fiber and its properties become clear.

Then, as the smallest component of paper product will be considered the proper cellulose fiber, studying its relation with surrounding.

3.2 **Wood anatomy**

Wood has been used for thousands of years, as a construction material and as a fuel. It is an organic material, a hard, fibrous structural tissue, natural composite of cellulose fibers (which are strong in tension) embedded in a matrix of lignin which resist compression.

As the microscopic properties of wood are studied thoroughly in paper industry and biology, as a scientific background for this work are adopted analysis and conclusions from doctoral thesis of Helena Halonen [20], Lorna Gibson [17] and the book Mechanics of Paper Products, which combines many relevant studies of referenced authors into one place, edited by Kaarlo Niskanen [31].

3.2.1 Microstructure

In trees, the wood consists of wood cells embedded in a matrix composed primarily of lignin and adhesive polysaccharides (pectin). The fibers are elongated wood cells that provide mechanical strength and water transport through openings called pits.

In softwood (e.g., pine and spruce), the fibers are long (2–4 mm), whereas in hardwood (e.g., birch and eucalyptus), the fibers consist of shorter (~1 mm) and stiffer libriform. The softwood fibers are more rectangular in shape (20–40 μm in diameter) compared with the rounder hardwood fibers (14–40 μm in diameter).

The growth in springtime (earlywood) is rapid, yielding large fibers with thinner cell walls (2–4 μm in Scandinavian softwood), whereas the growth in summertime (latewood) is slower, yielding denser fibers with thicker cell walls (4–8 μm in Scandinavian softwood).

3.2.2 Ultrastructure

The fibre cell walls have a layered structure, as shown in Fig. [III / 3], which is an illustration of the hierarchical structure of wood from the tree to the cellulose molecule.

As indicated in Figure [III / 3] the cell wall is composed of different layers, which are designated as the primary cell wall (P), the outer secondary cell wall (S1), the middle secondary cell wall (S2) and the inner secondary cell wall (S3). The layers are complex biocomposites made of cellulose fibril aggregates embedded in a matrix of hemicellulose and lignin.

The layers differ both in structure and composition. The primary wall, the thinnest cell-wall layer, is rich in pectin and lignin and is reinforced by a nearly random network of fibril aggregates. The secondary wall is the principal part of the cell wall and, as previously mentioned, consists of three layers: a thick middle wall and thin outer and inner walls. In the secondary wall, the fibril aggregates are aligned almost in parallel and wind as a spiral along the fibre axis.

In the thick S2 layer, the fibril orientation is nearly parallel to the fibre axis, while in the S1 and S3 layers, the fibrils are oriented nearly perpendicular to the fibre axis. "*(...)The proportions of cellulose and hemicellulose are greater in the secondary layer than in the primary wall, and the quantity of lignin, which dominates between the cells, decreases approaching the lumen. Due to the thickness of the S2 layer, this wall has the primary influence on the characteristics of the fibre and materials made thereof*".[20]

Fig. [III / 3] - Hierarchical structure from the tree to the cellulose molecule (Illustration: Airi Illistre). [20]

3.3 **Cellulose**

Cellulose is a long and linear homopolymer composed of 5 000–10 000 β-D glucopyranose units linked by (1→4)-glycosidic bonds with cellobiose as the repeating unit Figure [III / 4].

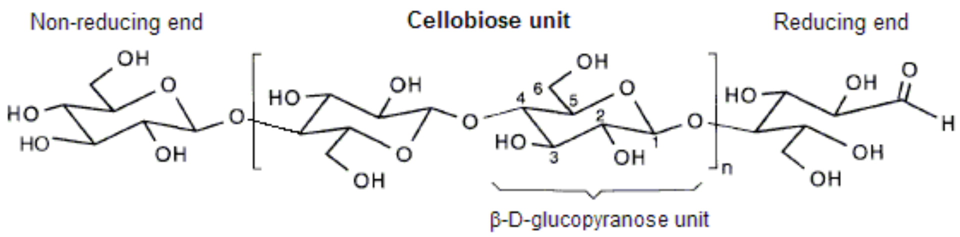


Fig. [III / 4] Molecular structure of cellulose. [20]

Although cellulose is a large molecule, it is too small to observe even with an electron microscope. The longest cellulose chain is approximately 5 μm long and has a diameter of approximately 6–8. (0.6–0.8 nm).

"*(...) The cell walls of plants are made up of just four basic building blocks: cellulose, hemicellulose, lignin and pectin. Cellulose is the main structural fibre in the plant kingdom and has remarkable mechanical properties for a polymer: its Young's modulus is roughly 130 GPa, and its tensile strength is close to 1 GPa Fig. [III / 5].*" [17]

The properties of hemicellulose and lignin are similar to common engineering polymers: lignin, for instance, has a modulus of roughly 3 GPa and a strength of about 50 MPa. Broadly speaking, the cell walls of plants are made up of cellulose fibers reinforcing a matrix of hemicellulose and either lignin or pectin in one or more layers, with the volume fraction and orientation of the cellulose fibers varying in each layer.

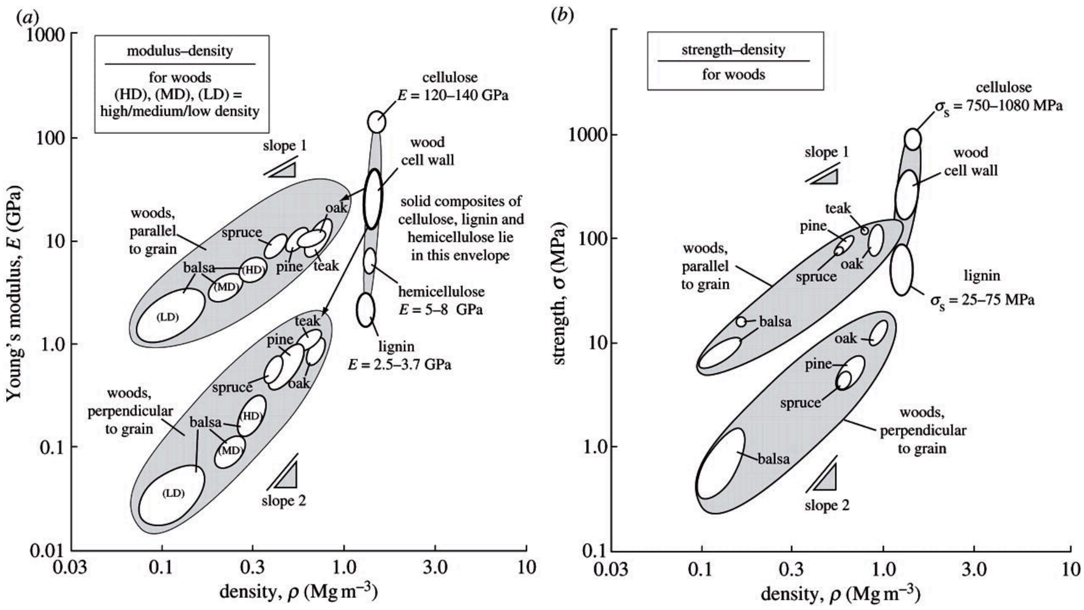


Fig. [III / 5] - (a) Young's modulus and (b) strength plotted against density for woods and their constituents. Adapted from Gibson. [17]

The geometrical structure of plant cells also varies, from the mostly honeycomb-like prismatic cells of wood to the foam-like polyhedra in the parenchyma cells of apples and potatoes.

"*(...) The variations in the hierarchical microstructure of plants (the microstructure at different length scales, including the volume fraction of each of the basic building blocks, the cell wall microstructure and the cellular structure) give rise to a remarkably wide range of mechanical properties, illustrated in Fig. [III / 6], which plots, on log–log scales, the strength against Young's modulus for three groups of plant materials: woods, parenchyma and arborescent palm stems.*" [45]

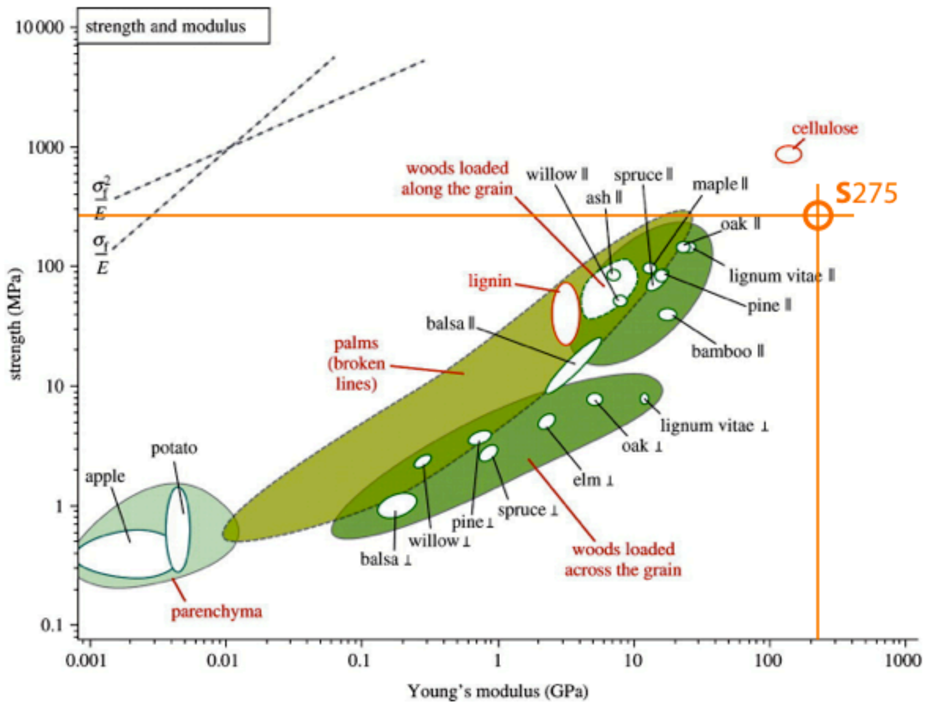


Fig. [III / 6] - Strength plotted against Young's modulus for selected plant materials. Note the large range in properties produced by varying the arrangement of the four building blocks (cellulose, lignin, hemicellulose and pectin) in the cell wall as well as the cellular structure. The properties of the cellulose and lignin are indicated in red. Adapted from Gibson. [17]

Observation 2

The main constituent of paper products are cellulose fibers. Provided information from Fig. [III / 5] and [III / 6] reveals the superior mechanical properties of cellulose ($E \approx 130$ GPa, $\sigma \approx 1$ GPa) in relation to all other wood constituents. From pure mechanical point of view, cellulose is the most valuable substance we can extract from wood. It is in the range of steel's S275 mechanical properties.

Paper certainly does not have similar properties to the steel, so it is interesting to explore the reason for that, considering that basic molecule chains have similar mechanical properties.

Cellulose molecules are basic constituent of fibers, so it is important to understand how do they form a fiber.

3.4 **Plant fiber structure**

"*(...) Even in an engineering context, it is helpful to consider that the plants, from which we derive wood and other fibers, are biological organisms. Fibers have specific functions in the plant organism, and these functions, together with growth aspects, explain the structure of plants. Plant fibers in trees and grasses (i.e., annual plants such as flax) are single cells. The fibrous shape indicates that they have a mechanical function in the plant.*"[31]

Fiber geometry provides anisotropy, and the load-carrying ability is high in the direction of fiber axis. In addition, the fiber cell wall itself is anisotropic due to the organization of its components. The cell wall is much stiffer in its length direction than in the transverse directions.

Fig. [III / 7] presents a micrograph of a plant fiber or cell. Softwoods (coniferous trees such as pine and spruce) are most relevant in the context of composites because they consist of long fibers called tracheids. Their length is typically 2–4 mm and diameter 20–40 μm, and thus the aspect ratio (length/diameter) is around 100. The lumen is the empty space at the center of the cell. The fiber cell wall consists of a thin primary wall layer and a thick secondary wall layer. The latter divides further into thin S1 and S3 layers and a thick S2 layer that occupies about 85% of the fiber cell wall thickness. An important structural feature is that the cell wall is composed by cellulose microfibrils with a diameter of 5–15 nm, depending on the plant. Cellulose microfibrils reinforce the cell wall and are oriented at a certain angle to the fiber direction (microfibril angle, MFA). The smaller the microfibril angle, the stiffer and stronger is the fiber. The S2 layer typically has MFA = 10–30º, but at chest height of the trunk the outer part in a mature coniferous tree contains tracheids (fibers) of very small MFA. This is the region of the tree that is subjected to high stresses when the tree trunk is bent by heavy winds.

The cell wall has an organization of a laminated composite material with cellulose microfibrils in a matrix of highly hydrated lignin-hemicellulose complex. Softwoods typically have around 42% cellulose, 27% hemicelluloses, and 28% lignin out of the dry matter and a few percent extractives (fatty acids and phenolics). The water content in a native wood fiber is around 30%. Most likely, the hydrated lignin-hemicellulose matrix is strongly associated with the cellulosic microfibril by physical adsorption of hemicelluloses. Lignin and hemicelluloses are also linked and form a polymer network. The mechanical behavior of a wet wood cell wall is poorly understood. It shows interesting features, including an impressive combination of strength, stiffness, and toughness despite its hydrated state.

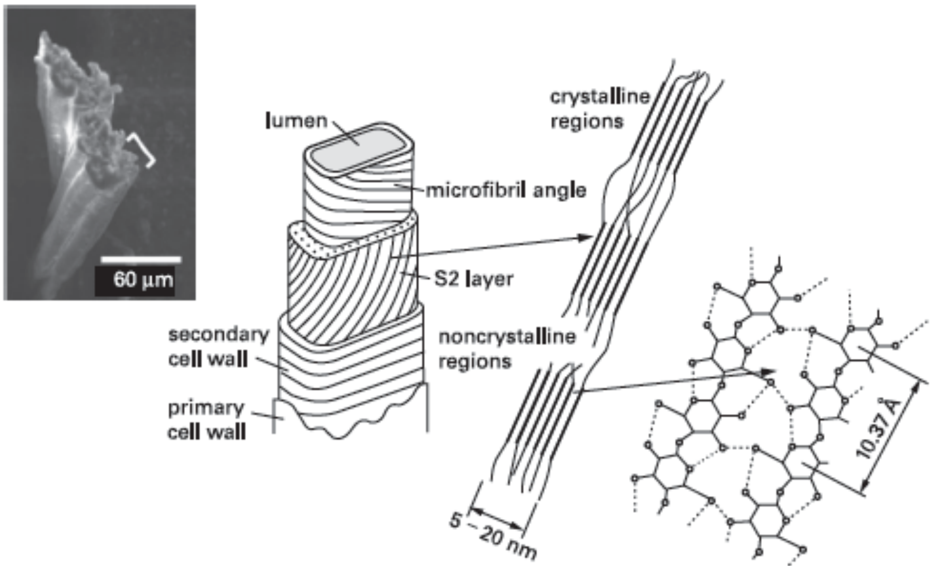


Fig. [III / 7] - Micrograph of a plant fiber cell (left). The cell wall structure consists of the primary cell wall; the secondary cell wall with the S1, S2, and S3 layers of different organization and microfibril angle of the cellulose(center); and the cellulose microfibril with ordered and less ordered regions (right). Courtesy of Prof. T Nishino, Kobe University. [31]

"*(...) In a mechanical property sense, cellulose microfibrils need to be stiff and strong because their main function in plant cell walls is to provide tensile performance. Obviously, wood tracheids also carry compressive stresses, but the tensile material function is still the most important one for cellulose in plant organisms. The estimated axial elastic modulus of the cellulose crystal is 134 GPa. It arises from the extended chain conformation of cellulose molecules, giving high density of strong inter-molecular covalent bonds, and strong intra-molecular hydrogen bonds that stiffen the molecule. The hydrated lignin-hemicellulose network, which constitutes the cell wall matrix, is amorphous in nature. In spite of some degree of hemicellulose orientation, the elastic modulus of the amorphous network is unlikely to exceed 1 GPa.*"[31]

Geometric features of some plant fibers, including the microfibril angle (MFA) and cellulose degree of polymerization (DP) (a measure of the molar mass or length of cellulose molecules) are presented in Table [III / 8]. The high DP of cellulose is helpful because it means that a lot of the strong covalent bonds have to be broken in order to break microfibrils of the cell wall. However, during the cooking of wood fibers into a chemical pulp, some degradation of cellulose DP takes place, and this will decrease the strength of cellulose. It is interesting to note that hemp, jute, flax, and ramie have very low microfibril angles. Although it is tempting to relate this to plant stem function, we have to keep in mind that these are plants used for thousands of years as fiber sources for textiles. As a consequence, the breeding of these grasses has been strongly focused on the production of stronger fibers, probably selecting for small MFA and high cellulose content.

It is also interesting to note the very large aspect ratio of grass fibers. In a practical context, it is difficult to process fibers that are 15 cm long (ramie). Usually the fibers used in textiles are made by spinning so that the plant fiber cells are intertwined into a continuous thread of larger diameter. Cotton is not a tensile material but has a seed hair function. Wood is very interesting due to its comparably low cost and the considerable infrastructure for harvesting and processing that is present in many regions of the world. The aspect ratio (length-to-diameter) is typically more than sufficient for biocomposite requirements.

Fiber	Width (μm)	Length (cm)	Aspect ratio	MFA	DP
Hemp	16–50	1.2–2.5	500–700	2.3°	9300
Jute	20–25	0.15–0.5	75–200	7.9°	n.a
Flax	11–20	1–3	900–1500	6°	7000–8000
Ramie	20–75	12–15	2000–6000	6°	10800
Cotton	15–30	2.5–6	1700–2000	28°–44°	15300
Wood	20–30	0.1–0.3	33–150	10°–40°	10000

Tab. [III / 8] - Geometrical parameters, microfibril angle (MFA), and cellulose degree of polymerization (DP) in some plant fibers (after Wainwright et al., 1982). [31]

Observation 3

Cellulose molecule is a long polymer with slender proportions, diameter around 0.6–0.8 nm, Young's modulus E ≈ 130 GPa and tensional strength $\sigma \approx 1$ GPa.

The cellulose fiber is a bundle of cellulose molecules, with different microfibril angles (MFA) in different layers. Under external loads, whichever directions they come from, it is not possible that all molecules and microfibrils work in pure axial direction, so elastic modulus of cellulose fiber must be lower than the modulus of a single molecule.

This explanation may be affirmed by this observation:

"*(...) Given the helical fibril structure of wood fibers, it is easy to accept that tension applied during drying can increase the axial alignment of the fibrils, which in turn leads to higher axial modulus. One can also follow the drying of single fibers under a microscope to see how they twist and bend if no tension is applied. In a paper sheet, the tendency for such deformations leads to reduced elastic modulus unless drying shrinkage is prevented.*" [31]

In Tab. [III / 9], some data about fiber properties are provided. We can see that elastic modulus of wood fiber is around 3,7 times lower (E=35 GPa) than cellulose molecule's elastic modulus (E ≈ 130 GPa).

Comparing the tensile strengths, the difference is even higher. The tensile strength of wood fiber σ_{max} = 120 MPa, is around 8,3 times lower than the strength of cellulose molecule $\sigma_{max} \approx 1$ GPa.

Fiber	Elastic modulus E (GPa)		Elastic modulus ratio, E_{dry}/E_{wet}	Tensile strength σ^{max} (MPa)		Tensile strength ratio, $\sigma^{max}_{dry}/\sigma^{max}_{wet}$	Breaking strain (%)	
	Wet	Dry		Wet	Dry		Wet	Dry
Hemp	35	70	2	n.a	920	n.a	n.a	1.7%
Jute	n.a	60	n.a	n.a	860	n.a	n.a	3.0%
Flax	27	80–110	3–3.7	880	840	0.96	2.2%	1.8%
Ramie	19	80	4.2	1080	900	0.89	2.4%	2.3%
Wood	n.a.	35	2	82	120	1.5		

Tab. [III / 9] - Elastic modulus, tensile strength, and breaking strain of some plant fibers in the wet and dry state. [31]

3.5 **Plant fiber properties**

The mechanical properties of plant fibers are interesting for estimates of the property potential of biocomposites. The elastic modulus of different fibers is controlled by the cellulose content and microfibril angle (higher cellulose content and lower MFA increase the elastic modulus). All plant fibers have significantly reduced elastic modulus in the completely wet state. However, the tensile strength is not significantly reduced because moisture increases the plasticity and toughness of the cell wall so that the fibers become less sensitive to defects.

The breaking strain ε_{max} of fibers is not very high because the cellulose molecules in microfibrils are in extended chain conformation, aligned with the fiber axis and cannot stretch very much without failing. Wood fibers with high MFA (occurring in so-called compression wood) are an interesting exception together with coir fibers because at high MFA the microfibrils can slide and reorient relative to one another, providing high ductility to the cell wall.

The wood products industry supplies many different types of wood fibers for different applications. It is interesting to consider the suitability of different fibers for new types of wood fiber biocomposites. Table [III / 10] lists the most common types of wood fibers, with comments on their characteristics. Due to the low cost, saw dust and other particles from saw mills and machining of wood are in widespread use in particleboards and melt-processed thermoplastic wood composites. However, because the typical aspect ratio of these particles is low (≤10), the reinforcement potential of the stiff wood fiber is not utilized.

In contrast, mechanical pulps such as TMP and CTMP have much higher aspect ratio (≈ 100) and have better reinforcement efficiency in biocomposites. The chemical composition in TMP and CTMP is fairly similar to wood. This may cause problems with odor (thermal degradation of hemicelluloses and lignin) or discoloration (extractives) problems in biocomposites that are processed at high temperature (e.g., melt-processing or compression molding). Bleached kraft pulps are more stable. They can also have high molar mass of cellulose, which gives good fiber strength. The hemicellulose content is usually significant since it may be hydrolyzed in high-temperature processing. Sulfite pulps can have very low hemicellulose content, but at the same time, the DP of cellulose is lower than in kraft pulps.

Wood fiber type	Chemical composition	Characteristics
Saw dust, wood flour	Similar to wood	Short aspect ratio, large size since the particles often are tracheid bundles
Mechanical wood pulp	Similar to wood (high yield)	Individualized fibers 20–30 μm in width and 1mm (hardwood) to 3 mm (softwood) in initial length, mechanically cut or damaged, little fiber collapse
Chemo-thermomechanical pulp (CTMP)	Low extractives content, otherwise similar to wood (yield 90%–93%)	Less mechanical damage compared with TMP
Bleached sulphate pulp (kraft)	Low lignin conc., typically 15% hemicellulose, 85% cellulose	Individualized, mechanically intact, collapsed after refining
Sulphite pulp	Low lignin conc., 4%–15% hemicelluloses, 85%–96% cellulose	Individualized, mechanically intact, collapsed after refining, lower cellulose molar mass than kraft pulp
Nanofibrillated cellulose (NFC)	Typically 4%–15% hemi-cellulose, depending on pulp source	5–15 nm in width and several micrometers in length

Fig. [III / 10] - Chemical composition and characteristics of wood reinforcement particles. [31]

Observation 4

After closer understanding of cellulose molecule and fiber properties, first summary can be made.

As a smallest particle of cardboard, it can be considered now a wood cellulose fiber. It's mechanical properties are around E = 35 GPa and σ_{max} = 120 MPa, but these numbers still do not represent real properties of final paper product, because of great influence which has a papermaking process on the end product properties.

In order to get closer to the final product's properties, it is necessary to understand the influence of papermaking process.

3.6 **Fiber mechanical properties in relation to the papermaking process**

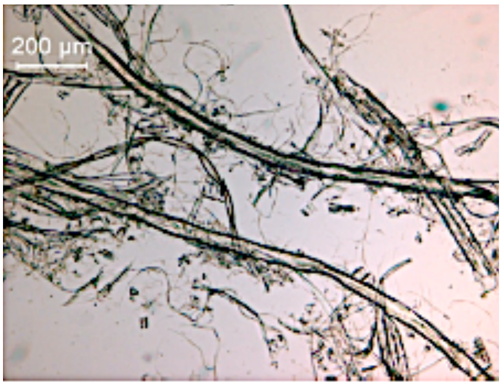
3.6.1 Preparation of papermaking fibers

When paper is manufactured from wood, one usually starts by cutting the wood into chips Fig. [III / 11]. The chips are then disintegrated in fibers either mechanically or chemically to prepare what is called pulp; depending on the process, the end product is mechanical pulp fibers or chemical pulp fibers. In the native wood, typical fiber dimensions are 1–3 mm in length and 20–40 µm in cross-sectional width.

Fig. [III / 11] - Pine wood chips prepared for papermaking. The grainy structure comes from the annual variation in wood growth. Chip length in the grain direction is 25 mm. Figure courtesy of Lisbeth Hellstr.m, FSCN. [31]

"*(...) In a typical mechanical pulp manufacturing process, the wood chips are sheared between rotating steel plates Fig. [III / 12]. The pattern of the plate surface is designed to optimize the pulp quality. Steam is applied to soften the lignin that holds fibers together in the wood material, and also the cellulose of the fiber cell wall, so as to reduce fiber damage in the disintegration process. Pressure and chemicals may also be used for this purpose. Depending on the specific manufacturing process, different types of mechanical pulp are obtained, such as TMP (thermomechanical pulp), CTMP (chemithermomechanical pulp), and their variants.*

In the chemical pulping process, wood chips are cooked with chemicals to dissolve the lignin that holds fibers together in wood. Also, water-soluble hemicelluloses get extracted in the process. Depending on the chemicals used, different types of chemical pulps are obtained, such as the kraft pulp (also called sulfate pulp) and sulfite pulp. The cooking process leaves the structure of fibers rather intact Fig. [III / 13] except for the removal of lignin and hemicelluloses." [31]



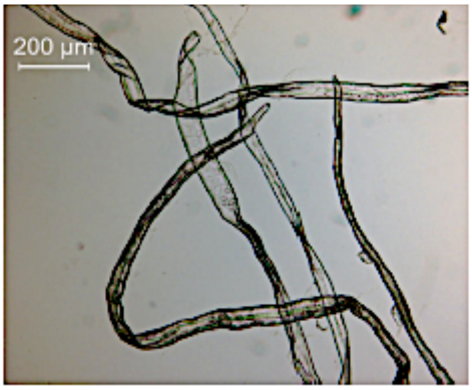


Fig. [III / 12, 13] - Spruce wood mechanical TMP pulp fibers, fiber fragments, and fines; Mildly refined chemical pulp fibers made of pine wood; courtesy of Boel Nilsson, SCA R&D. [31]

A typical yield of the chemical pulping process is slightly more than 50%, meaning that about half of the original dry mass of wood is retained in the fibers (compared with mechanical pulping where the yield is usually more than 90%). In chemical pulping, the chemicals dissolved from the wood material have been traditionally used for energy. However, recently increasing development efforts have been directed to various biorefinery concepts that convert the extracted chemicals to renewable fuels of polymeric raw materials.

After the fibers are separated, both chemical and mechanical pulp can be bleached with chemicals to increase the whiteness of the final product. Then the pulp is treated further in a mechanical process called refining or beating , which increases the flexibility and conformability of the fibers and opens up the fibrillar structure of the fiber surface. This is necessary to achieve good bonding between the fibers so that the resulting paper has sufficient strength. Especially in the mechanical pulping process a large fraction of the fibers is damaged and broken into fragments Fig. [III / 12].

Sections of the fiber wall structure break off as flat lamella and in narrow ribbon-like fibrils; these small fiber fragments are called fines. The fragmentation of fibers in mechanical pulping is intentional. Smaller particles give a more uniform paper structure, reduce transparency, and improve the sharpness of print on the paper. Chemical pulping causes some fiber damage also, but not as much as in mechanical pulping. Thus, chemical pulp is generally stronger than mechanical pulp. Also, because lignin and some of the hemicelluloses are removed, chemical pulp does not turn yellow as easily as mechanical pulp when exposed to light or heat.

After the pulp manufacture, one adds other components, such as mineral fillers and chemicals, to obtain a water-based furnish ready for papermaking. Fillers increase the opacity and whiteness of paper. Chemicals are added to help retain the fines particles of pulp along with the fibers when water is removed on the paper machine (“retention aids”), to improve bonding between fibers (“bonding aids”), and to control ink penetration into the paper (“sizing”). Tuning of the pulp properties and furnish composition is the main method used to tailor paper properties.

Observation 5

If the paper product is intended to be used as a structural material in architecture, it is more important that fibers provide good mechanical properties, such as a high tensional strength and elastic modulus, than fine texture and white color.

Therefore, as fibers in chemical pulp are mechanically intact, it is of interest to pay attention to the fibers origin in paper products, specially if there is intention to recycle paper products and convert them into structural elements.

In Table [III / 10] we can see that the sulphate (kraft) pulp has the optimum properties in terms of fibers resistance, length and cellular molar mass, which helps to understand why the main component of cardboard is chemically extracted (kraft pulp) fiber, providing excellent resistance properties to the material.

3.6.2 Pulp

There are some very important parameters which define the pulp. Fiber length, brightness and pulping process are the three most important ones.

Cellulose fibers have tendency to form molecular linkages between them in the presence of water, so once the water evaporates, the fibers remain bonded. Pulp strength is directly proportional to fiber length. Longer the fiber is, more linkages per fiber can be made, which means that stronger material will be obtained. Softwood (cold climate woods) pulps in general have longer fiber compared to hard wood (warmer climates woods) pulp.

Brightness is important for printing papers, so process as bleaching is of interest to obtain brighter color. Bleaching can additionally decrease the strength of the fibers and the mass of the pulp, so it is better to avoid very bright pulps for making a structural material.

As mentioned earlier, the optimum pulping process for making a structural material is Kraft (chemical) pulping. Comparing to mechanical and semi chemical pulp, chemical pulps (Kraft pulps) have higher fiber length, when made from same wood. More fibers get damaged and shorten by mechanical than chemical action.

3.6.3 Kraft Pulp

Chemical pulp is produced by digesting wood by sulfate process. Lignin binds the cellulose fibers together, and in the chemical process, heat and chemicals break down the lignin without degrading the cellulose fibers seriously. Kraft pulp is used mainly for high resistant, packaging papers.

3.6.4 Recycling

Since paperboard and cardboard are both paper material, they can be recycled, but cardboard boxes are much easier to recycle in comparison to paperboard. Since cardboard boxes are free of wax or kaolin clay, they are pressed into bales and transferred to manufacturers directly, so they can be shredded and mixed with water to create new fiber for new cardboard products. No sorting is required unless cardboard boxes are contaminated with food remnants such as grease or oil. Paperboard, on the other hand, has a more complicated recycling process. Seeing as it is often used to contain liquid and other food products, and most of the time will contain foil or wax, it will have to undergo a de-waxing and de-foiling process before it goes into a recycling machine. This type of paper product should not be mixed with cardboard when brought to recycling centers and is usually mixed with regular paper, or if wet or soiled, with compost.

Every recycling process damages the fibers. Fibers can be recycled up to ten times, when they start to be too short to form bonds between them. In order to maintain enough quality, in recycled pulp it is often added a portion of virgin pulp.

3.6.5 Tensile strength of pulp

This is not the tensile strength of individual fiber, which is even higher than or comparable with steel. The tensile strength discussed here is maximum strength of randomly oriented pulp fiber when formed in a sheet. This tensile strength gives an indication of the maximum possible strength of pulp beaten under ideal condition. This again is an indication of which level of tensile strength can be achieved in real paper making environment.

3.6.6 Effect of the paper machine

Another important factor which determines properties of final paper product is the continuous process of making paper. Most modern papermaking machines are based on principles of the Fourdrinier Machine.

"*(...) Figure [III / 1] demonstrates the structure of a paper machine, here cut in two parts to fit the figure on the page. The total length of a paper machine is typically a few hundred meters. The machine begins at top left with a forming section where the furnish at about 1% solids content is spread from a "headbox" (red in Fig. [III / 2]) on a moving wire. The low solids content is necessary so that fibers can be spread uniformly on the wire. Water is then removed by suction units (yellow) through a top and bottom wire and by wet pressing, where cylinders (dark green) press the wet paper web between two wires or felts. The forming and pressing sections* *together are called the "wet end" of the paper machine. When leaving the wet end, the solids content of the web is around 50%. Then the paper web is moved to the dryer section and pressed against hot cylinders so that water evaporates (red). A large number of dryer cylinders are needed because of the high speed of the process, which can reach 2000 m/min. Bonding between fibers forms spontaneously when water disappears from the web. In the "dry" end of the paper machine (bottom half of Fig. [III / 1]), water suspensions of sizing and pigments can be spread on the web surfaces to improve paper appearance and performance in printing (the blue rolls on the left). Further drying is then needed before winding to paper rolls. There is no coating or calendaring in the papermaking line of Figure [III / 1] because it is designed for containerboards that do not need high surface quality. In printing papers and packaging boards, one or several mineral coating layers can be used to maximize the product quality."* [31]

The initial forming section of the paper machine determines the network structure of fibers in the paper Fig. [III / 14]. The fiber distribution is disordered but not completely random because the fibers have a tendency to form bundles or flocs. Furnish is diluted to less than 1%, and turbulence is induced in the headbox and on the wire to reduce the flocculation of fibers.

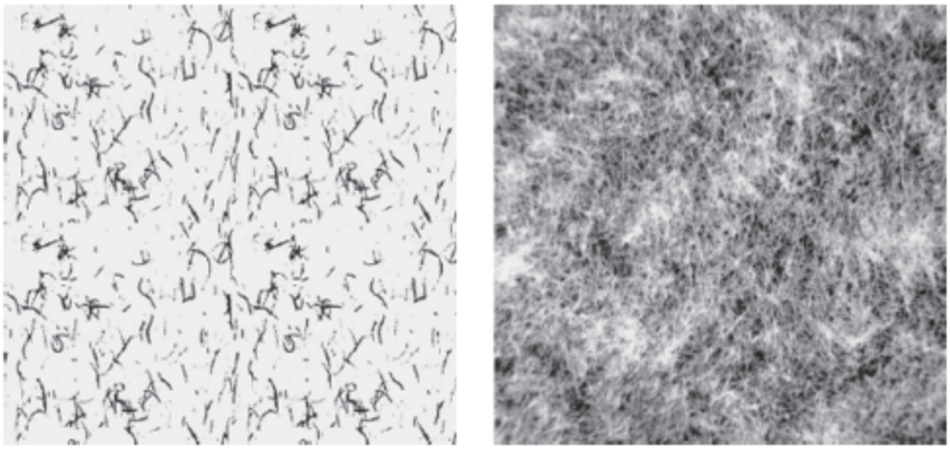


Fig. [III / 14] - Surface image of a paper sheet containing a small fraction of fibers dyed black (left), and a layer split from a sheet, showing fibers and fiber bundles (right, courtesy of Pekka Pakarinen). [31]

The nonuniform in-plane mass distribution of paper is called formation. It can best be seen with bare eyes in thin paper grades such as newsprint or some office papers. Aside from being a visual imperfection, formation can cause out-ofplane deformations to paper if the moisture content changes, and in rare cases, it can reduce the strength properties of paper, such as creep resistance.

Fiber orientation in paper arises from the forming process. A small speed difference is generally needed between the wire and the furnish jet that comes from the headbox to enhance smooth spreading of the furnish and thereby reduce the nonuniformity in mass distribution. At the same time, the speed difference creates a shear field through the thickness of the furnish layer, which in turn rotates fibers more parallel to the machine direction (MD). The anisotropy of fiber orientation is one of two factors that cause anisotropy in the mechanical properties and hygroexpansion of paper (Niskanen, 1993), the other being the drying effect discussed below.

On the dryer section of the machine, the paper web shrinks because water is removed from the fibers. Earlier in the process, water is removed only from the pore space between fibers. At this stage of drying, a tension must be applied on the web to prevent fluttering and to improve contact with the drying cylinders. The drying tension on the paper machine prevents paper shrinkage in the MD, which occurs almost exclusively in the CD. Drying tension versus shrinkage is the second factor that influences the anisotropy in the mechanical properties and hygroexpansion of paper.

On a broad paper machine, slight cross machine (CD) deviations can occur in the flow direction of furnish so that the local symmetry axis of the fiber orientation distribution may be a few degrees off the machine direction. The nonzero fiber orientation angle can cause diagonal curl in products where paper or board is used in sheet form, and this can lead to, for example, paper jams in a copy machine.

The direction of initial water removal creates a z-directional profile of fines and filler concentration in paper. The smaller particles are flushed with the water, generally toward the wires. Because of the flushing, layers close to the wire surfaces can be depleted of fines and fillers. A ZD variation arises even in the fiber orientation distribution because the shear field in the suspension layer changes as the water removal progresses.

The wet pressing stage of a paper machine determines the thickness and density of paper. Intensive wet pressing is favorable for water removal and reduces the energy needed in the dryer section, but it also leads to a densification of the paper. Low paper thickness gives low bending stiffness, which is often a problem, for example, in the handling of paper sheets or in the strength of paperboard boxes.

The forming and wet pressing stages of the paper machine determine the structure of paper from centimeters down to the microscopic fiber network structure.

Summary on Part 1

The idea of this part of work was to synthesize the paper industry studies and understand the microstructure of paper products.

First, the approach went from outside towards inside, getting to the properties of the smallest particle, the cellulose molecule, which has very high mechanical properties ($E \approx 130$ GPa and $\sigma \approx 1$ GPa), almost comparable to steel.

After that, the direction changed towards outside. Analysis of the cellulose fiber structure helped to understand it as a bundle of very slender cellulose molecules grouped into microfibrils, which are the main constituent of the cell walls. The orientation of micro fibrils is not in pure axial direction, but each cell wall has fibrils under different angle (MFA). Under external loads, it is not possible that all fibrils work in pure axial direction, which most probably is the reason why the cellulose fiber has lower mechanical properties ($E = 35$ GPa and $\sigma_{max} = 120$ MPa) than the cellulose molecule.

Insight into papermaking process revealed some important factors to count on. Pulp obtained by chemical sulphate process (Kraft pulp) has superior mechanical properties than mechanical or semi chemical pulp, so it is important to pay attention on fibers' origin, specially if coming from recycled paper products. At the same time, every recycling process damages the fibers, so it is important to add a portion of virgin fibers to maintain good mechanical properties of the end product.

Understanding the cellulose fiber and pulp mechanical properties is not enough to predict the behavior of paper products. Papermaking process has important influence in formation of cellulose fibers web, which determines important paper properties. Fibers orientation, mostly in machine direction, and tension applied during the drying process determine anisotropic behavior of paper.

During the papermaking process, the linkage between cellulose fibers is formed, and after the drying process fibers stay bonded. The strength of bonds and random orientation of fibers are additional factors which influence the mechanical properties of the final paper product.

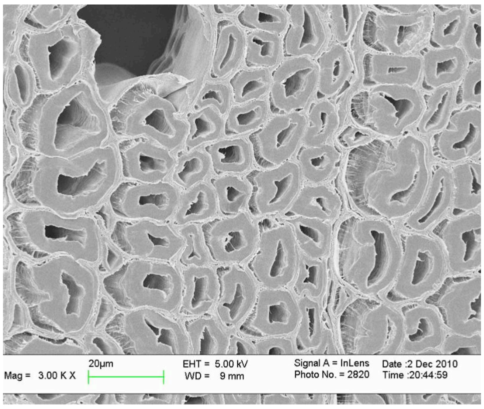
The end product made of Kraft pulp is the base paper product used for cardboard production. Usually it is called linerboard. The properties of any type of cardboard will directly depend on the mechanical properties of the linerboard it is made from. Therefore, the next focus is a study of mechanical properties of Kraft paper.

Part 2

4. Mechanical properties of Kraft paper

4.1 **Paper properties**

There are three important factors which determine the mechanical properties of paper. The properties of fibers Fig. [IV / 1], interfiber bonding Fig. [IV / 2] and geometrical disposition of the fibers Fig. [IV / 3].



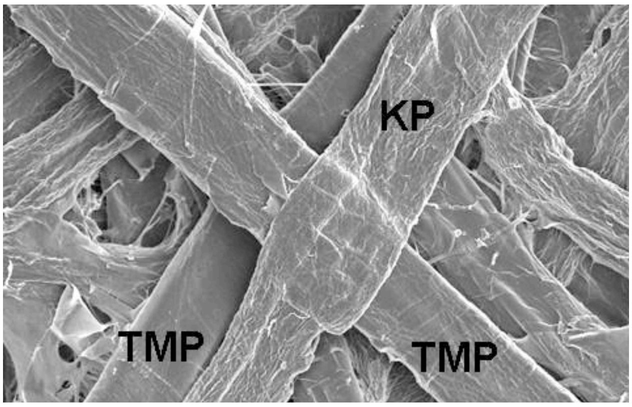
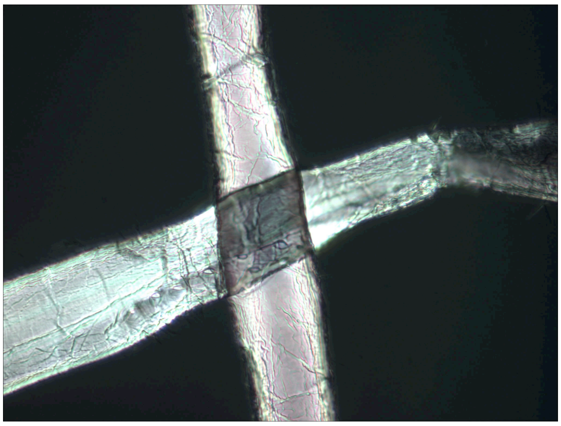


Fig. [IV / 1] - (a) Cellulose fibers in wood. (b) Difference between Kraft pulp (KP) and Thermo mechanical pulp (TMP).



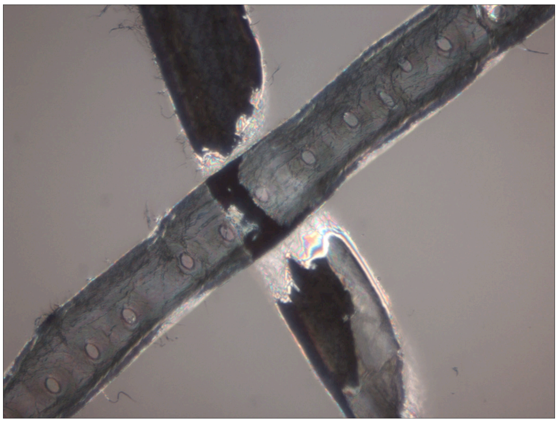
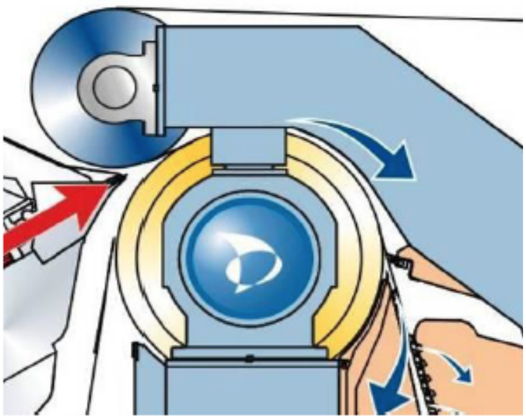


Fig. [IV / 2] - (a) Full interfiber bond. (b) Partial interfiber bond.



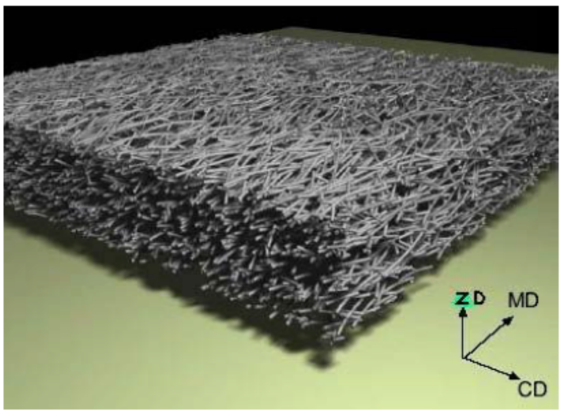


Fig. [IV / 3] - (a) Speed difference between the wire and the furnish jet that comes from the headbox. (b) Paper 3D structure. [02]

It is important to know how different fiber types and other components influence the properties of paper. In laboratories, when sheets are produced for experiments, even having the same composition as machine produced ones, they will not have the same properties, because paper properties do not depend only on the composition but also on the papermaking process. Laboratory prepared paper is different than paper prepared on paper machine.

"*(...) The most serious problem in the microscopic analysis of paper properties is the lack of real, measured data on the fiber properties. Measurement methods and experimental data are available primarily for the geometric fiber dimensions. Only some scattered data are available for the mechanical properties of fibers and interfiber bonds. Those data are of questionable value because the mechanical properties of fibers and bonds in a paper sheet are influenced by the papermaking process. The effect of the papermaking process on the fiber properties is a very important special feature of paper. One may be completely mislead if one assumed that paper can be described as a network of ideal fibers that have some prescribed inert mechanical properties.*" [31]

As paper is a web of a randomly oriented interconnected fibers, each series can have micro structural variations. That can result in slightly different mechanical properties with every new furnish or different papermaking machine. It is almost impossible to predict precisely a geometry of fiber network structure, but it is very helpful to study microstructural mechanisms on some examples.

Interesting considerations in this chapter are the statistical geometry of the network structure, elastic modulus, the mechanisms of stress transfer and fiber activation, microscopic fracture process, hygroexpansion of the fiber network and analysis of experimental mechanical properties.

4.1.1 Fiber network structure [31]

The structure of paper is obviously significant when one considers the mechanical properties. Fibers make up paper only if the fibers bond to each other. More bonds per fiber means, in qualitative terms, stronger paper. Thus, before we can focus on the mechanical properties of the fiber network, we have to determine how to describe the network structure. Of particular importance is the length of fiber segments between neighboring bonds on a fiber.

In the ideal sense, the structure of paper is a planar random network of slender fibers. The length of the fibers varies and is typically between 1–3 mm, much higher than the typical thickness of a paper sheet, which is 0.1 mm. The length of the fibers is also much larger than their width and thickness, which range from 10–50 µm.

Discussion of paper structure concentrates on this ideal type of planar network structure, which consists of fibers that are, for most of their length, aligned parallel to the plane of the paper sheet, while making some bends up and down to conform to the shapes of the neighboring fibers.

The amount of fibers per unit area of paper is characterized by basis weight , the mass per unit area. Typical basis weights of printing papers and office papers are 40–100 g/m^2 , while paperboards are heavier, with basis weights extending to 400 g/m^2 and higher. Fibers are not arranged in distinct layers, but a good rule of thumb is that if one would make a point-wise measurement through the thickness of a typical office paper, then approximately 10 fibers would be detected at any given point because the basis weights of fibers are 5–10 g/m^2 .

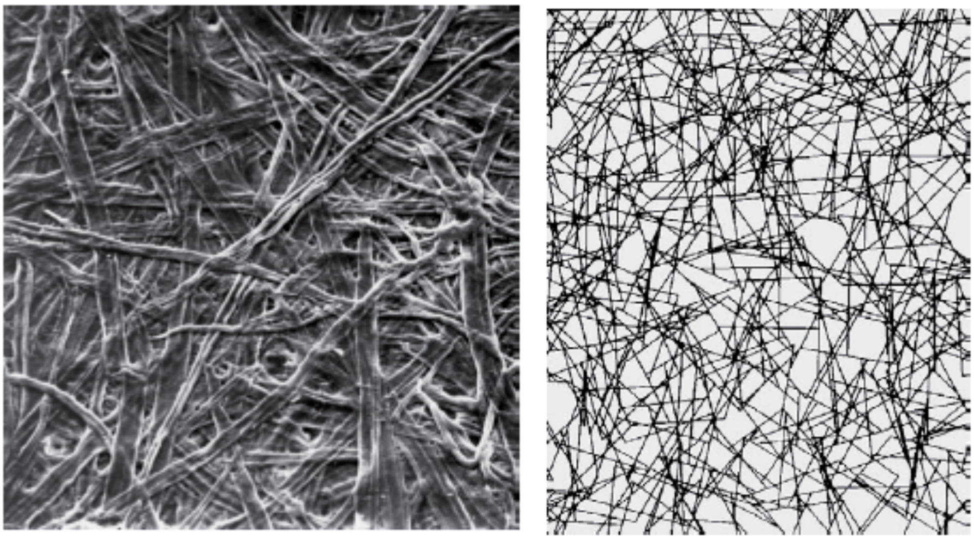


Fig. [IV / 4] - (a) SEM image of the surface of a paper made of chemical pulp, approximately 1 mm^2 in size. (b) Two-dimensional approximation of paper structure. Not shown are the “dangling” free ends of fibers that extend beyond the last inter-fiber contacts. [31] [01]

A particularly simple approximation of the fiber network structure of paper is one where the thickness and width of fibers is ignored. The result is a two-dimensional random fiber network of the kind shown in Fig. [IV / 4]. The crossing points or “bonds” between fibers divide the fibers into segments. These fiber segments and the bonds between them control the mechanical properties of the paper.

The length distribution of such fiber segments is exponential. The mean segment length in this ideal two-dimensional case is inversely proportional to the total fiber length per unit sheet area. External loads are transferred from fiber to fiber through the bonds between fibers. As the number of bonds per fiber increases, fiber segments become shorter, and the network becomes stiffer and stronger.

The applicability of the statistical geometry model of Kallmes and Corte (1960a, 1960b) is limited to paper sheets of very low basis weight. At basis weights above a few g/m^2 , the limited conformability of real fibers prevents inter-fiber bonding at every point where the planar projections of two fibers cross. As a result, open space between fibers forms also in the thickness direction of the sheet. In the basis weight range of real paper, above 40 g/m^2 , the length of fiber segments is controlled by the paper density and not by the basis weight.

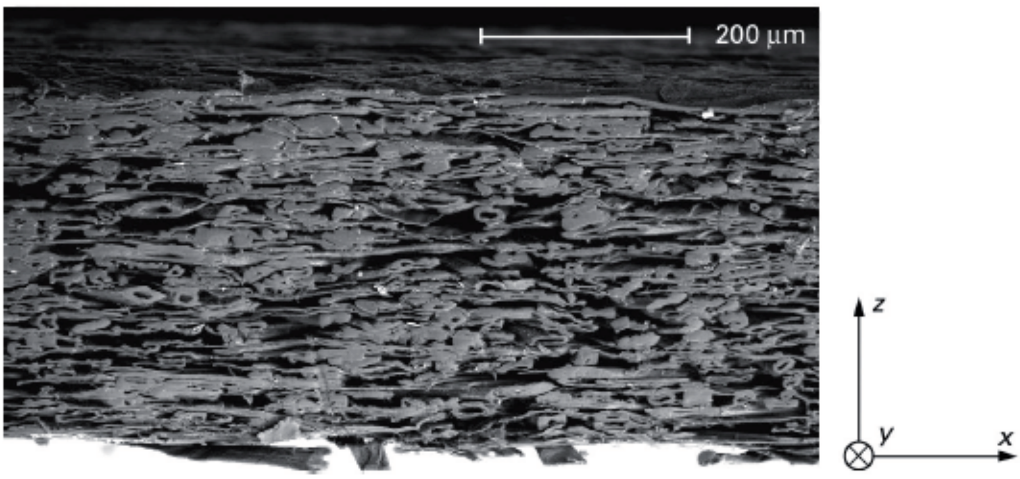


Fig. [VI / 5] - SEM picture of cross section of paperboard, showing the fiber network and open space between fibers in thickness direction.

Observation 6

In Fig. [IV / 1] (b), we can see clear difference between Kraft and thermo chemical pulp. In Kraft pulp, the lignin and hemicellulose from cell layers are totally dissolved, which leaves cellulose fiber much more adaptable than fiber from thermo chemical pulp.

In Fig. [IV / 2] we can see the importance of full bonding between fibers. Better the bonding between fibers, stronger will be the paper.

In Fig. [IV / 5] we can see that paper is not perfectly planar network (as it can appear macroscopically), and fibers have to be adaptable in Z direction as well. Higher the fiber adaptability, interfiber bonding will be easier.

This is one more advantage for use of chemical pulp to make structural elements.

4.1.2 Paper as an engineering material

Randomly organized network of fibers is very complicated to put in numbers. Nevertheless, as mentioned earlier, overall influence of papermaking process determines certain dominant properties which can be recognized in every paper.

Coordinate system, elastic constants and basic values of mechanical properties of paper products are adopted from Mechanics of Paper Products [31].

Paper is a thin, almost two-dimensional material. Everyday papers, such as office paper and newsprint, have a thickness of 0.1 mm. The mass per unit area of paper, called the basis weight , is usually between 40 and 100 g/m2 depending on the type of paper. Specially prepared paper can have a thickness as low as 0.01 mm and a basis weight of a few grams per square meter. On the other end, paper material used for book covers or fixtures to display products in stores can be more than 1 mm thick. Thick paper grades are called board or paperboard. The trade terminology for paper and board grades refers primarily to the applications where the materials are used, not to their structure. Paper is a general term used for all kinds of paper and board materials.

A paper machine creates a continuous web that is 5–10 m wide. A finished roll may contain 10 km of paper. The coordinate system used throughout this book is defined in Fig. [IV / 6] . The running direction of the web is customarily referred to as the machine direction (MD), and the lateral direction as the cross-machine direction (CD). The thickness direction is the Z-direction (ZD).

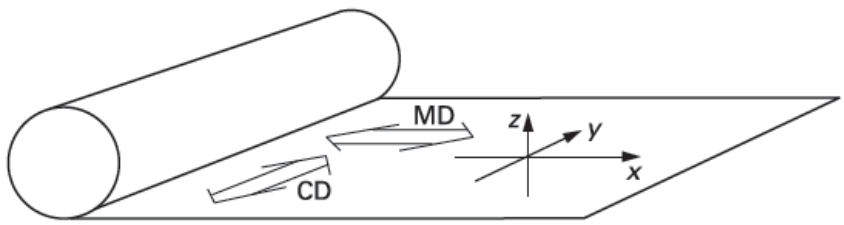


Fig. [IV / 6] - The coordinate system for paper. [31]

4.1.3 Elastic constants

The elastic constants give the stress to strain relation for paper when the performance is linear elastic. In the general 3D case, the state of stress is defined by the six independent stress components: the three normal stresses, σx, σy, and σz, and the three shear stresses, τ τ xy yx, τ τ xz zx, and τ τ yz zy (see Fig. [IV / 7]).

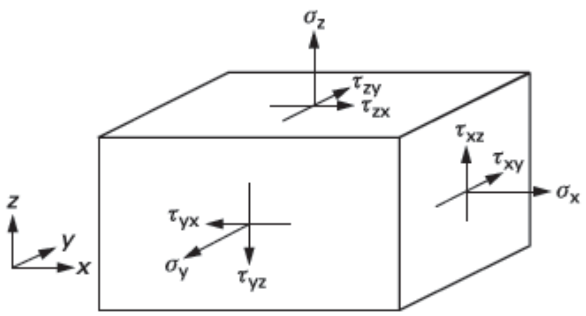


Fig. [IV / 7] - The stress components in a 3D state of stress. [31]

A positive value of shear stress τ ij corresponds to stress acting on the surface with its normal in the positive i-direction and directed in the positive j-direction. Because of moment equilibrium, shear stresses are equal in pairs, τ τ ij ji = . The alternative notations, σMD , σ1 , σ11 , or σxx etc are sometimes used instead of σx etc when the coordinates coincide with MD etc.

The state of strain in the 3D case also is defined by six components, the normal strains ε i , and the shear strains γ ij . The strains referred to in this book are the conventional small strain theory engineering strains. This means that the normal strains are defined as elongation Δl divided by the initial length l , and the shear strains are given by a sum of two deformation angles expressed in radians, for example, xz xz zx.

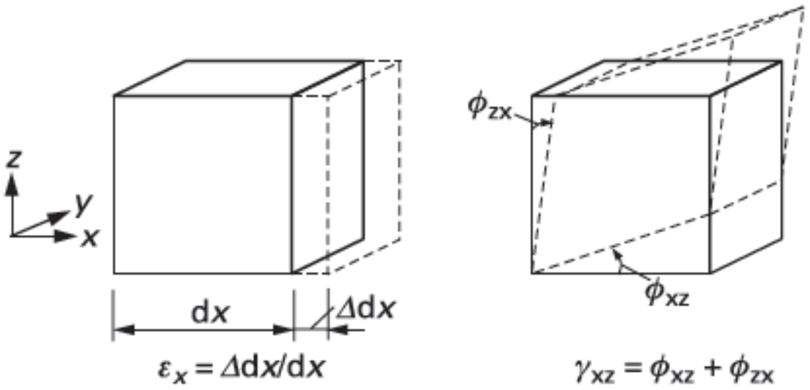


Fig. [IV / 8] - The normal strain ε x and the shear strain γxz in a 3D state of small strain. [31]

Unlike many other materials, the elastic modulus E of paper is significantly anisotropic. This arises from the manufacturing process, giving Ex > Ey. The anisotropy between the in-plane and thickness directions comes from the low thickness of paper. Because a typical fiber's length, 1–3 mm, is more than 10 times larger than paper thickness, fibers must be aligned in the plane of the paper. The z-directional straining of paper creates primarily transverse stresses in fibers, whereas in-plane straining creates longitudinal stresses. The longitudinal elastic modulus of fibers is larger than the transverse modulus.

A reasonable approximation is that the anisotropy of paper is orthotropic, that is, the stiffness properties are symmetric with respect to the x , y , and z axes, even though there may be a slight deviation in the symmetry axes because of skewness in fiber orientation.

4.1.4 Typical stiffness values of paper

Table [IV / 9] shows a collection of directly measured values of the elastic stiffness parameters for a few paper grades. Many values are missing because of measurement difficulties caused by the small thickness of paper. Various estimation schemes have been developed to escape direct measurement.

It demonstrates that the ZD stiffness of paper is generally low compared to the in-plane values. The negative value of the Poisson ratio ν_{xz} for the paperboard shows that uniaxial tensile loading in MD increased thickness in this case, which is not uncommon. In compression, at least the elastic moduli, perhaps even the Poisson ratios, are usually equal to the corresponding tensile values.

The high density of the coated paper is caused by the coating. Without the coating the paper would have similar density as the other samples. In general, the density of paper is between 300 and 900 kg/m^3 . The in-plane elastic modulus usually increases with density and ranges from 1000–9000 MPa when the effect of anisotropy is removed by averaging over MD and CD.

	Paperboard (Persson, 1991)	Carton (Baum, 1987)	Linerboard (Baum, 1987)	Coated paper, middle of web (Stålne, 2006)	Coated paper, web edge (Stålne, 2006)
Density, kg/m^3	640	780	691	1140	1140
MD modulus E_x, MPa	5420	7440	7460	7690	7660
CD modulus E_y, MPa	1900	3470	3010	3050	2570
ZD modulus E_z, MPa	17	40	29		140
Poisson ratio ν_{xy}	0.38	0.15	0.12	0.33	0.27
Poisson ratio ν_{xz}	–2.20	0.008	0.011		
Poisson ratio ν_{yx}	0.14			0.07	0.10
Poisson ratio ν_{yz}	0.54	0.021	0.021		
Poisson ratio ν_{zx}	0.05				–0.04
Poisson ratio ν_{zy}	0.05				0.03
Shear modulus G_{xy}, MPa	1230	2040	1800	1910	1820
Shear modulus G_{xz}, MPa	8.8	137	129		
Shear modulus G_{yz}, MPa	8.0	99	104		

Tab. [IV / 9] Measured values of elastic stiffness parameters in tensile loading for some machine made papers. [31]

Adopting values of linerboard from Tab. [IV / 9], property comparisons with other categories of materials is helpful. In a property chart, introduced by Michael Ashby [05], material efficiency of specific structures can be compared for different classes of materials.

The efficiency of tensile members is given by the ratio of elastic modulus and density (E/ρ). A higher value for this index gives a lower-weight tie for the same stiffness.

The efficiency of a beam loaded in bending is measured by the index $E^{1/2}/\rho$.

The corresponding index for flat plates loaded in bending is $E^{1/3}/\rho$.

Three stiffness guidelines corresponding to these indices are plotted in Fig. [IV / 10] together with the elastic modulus and density data for different material categories, all on log-log scales to facilitate comparison.

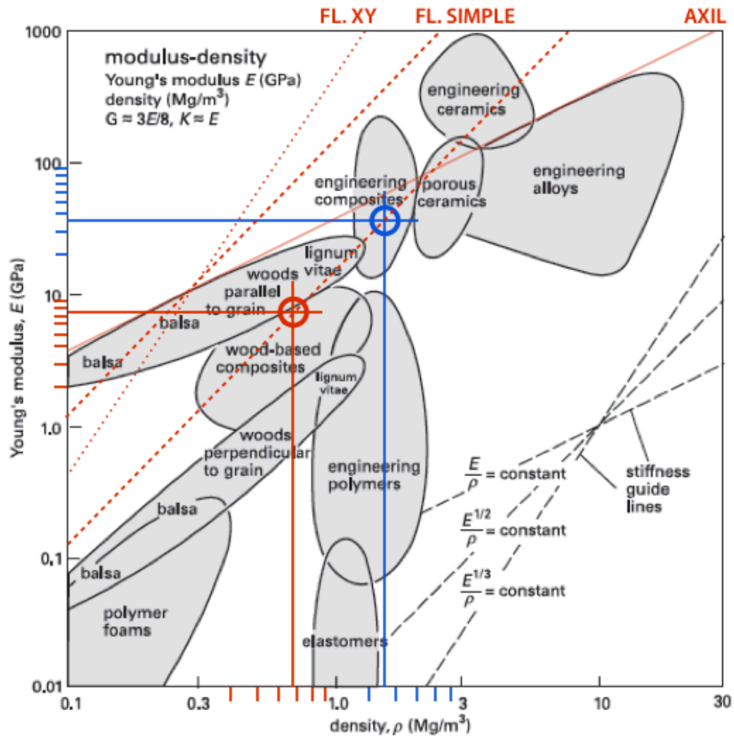


Fig. [IV / 10] - Elastic modulus as a function of density for different material categories, plotted on log-log scale. Note the materials efficiency guidelines explained in the text (Reprinted from Wegst and Ashby (2004) with permission from Taylor & Francis). Red circle represents linerboard properties (ρ = 691 kg/m^3 ; E_x = 7,46 GPa). Blue circle represents cellulose fiber properties (ρ = 1500 kg/m^3 ; E_x = 35 GPa). Edited by the author.

Observation 7

Previous analysis of cellulose fiber properties and its origin reveals that cellulose Kraft fiber is mechanically the most efficient component we can extract from wood in order to produce strong paper.

The red circle in Figure [IV / 10] represents the material made of most efficient substance extracted from wood (Linerboard), but surprisingly, its overall efficiency is just under the group of woods.

If we imagine hypothetic case in which we could make completely solid paper providing it with properties of cellulose fiber, its representation would be the blue circle on a diagram. Its elastic modulus is 4,7 times higher than Linerboard's. Its efficiency in tension is higher, but in bending it remains the same, because the density of material doubled.

This tells us that what we should look for in structural paper is not only the purest quality of well bonded fibers, but the mechanism which enables the possibility to obtain the highest elastic modulus with lowest material density. It can be observed though, in figure [IV / 11], that elastic modulus in ZD increases with increase of density.

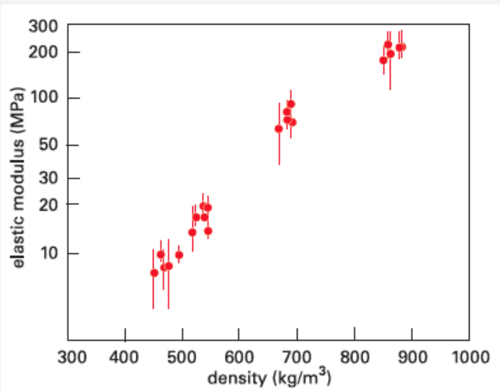
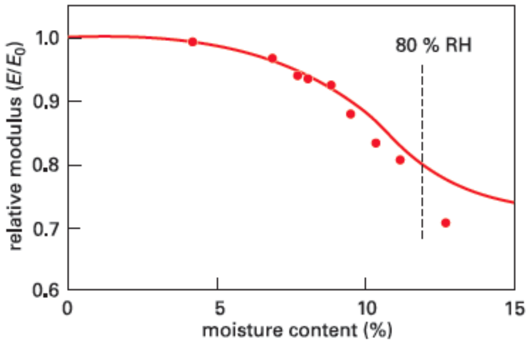


Fig. [IV / 11] ZD elastic modulus (logarithmic scale) of laboratory sheets against density for mechanical pulps (density ca. 500 kg/m3) and chemical pulps (density > 700 kg/m3), using data from Girlanda and Fellers (2007).

4.1.5 Moisture effect on paper

Water acts as a softener of paper. Thus, the elastic modulus of paper depends on the moisture content Figs. [IV / 12] and [IV / 13]. Ultimately at high moisture contents, the modulus of paper goes to zero as the bonding between fibers opens, and one returns to a state that prevailed when drying started in the papermaking process. We note in passing that it is this reversibility of the papermaking process that makes the recycling of paper possible.



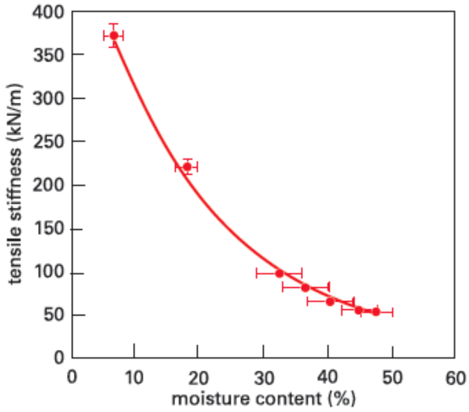


Fig. [IV / 12] - Elastic modulus against moisture content for a set of laboratory sheets. The modulus values are given relative to the value in dry paper (dots). The curve shows a theoretical prediction. Reprinted from Salm.n et al. (1984) with permission from Elsevier. [31]

Fig. [IV / 13] - Tensile stiffness against moisture content for a machine-made paper, measured with a cyclic small-strain excitation. Tensile stiffness is equal to elastic modulus multiplied by paper thickness, the latter being a slightly increasing function of moisture content. Drawn using data of Ketoja et al. (2007). [31]

The softening effect makes paper increasingly visco-elastic and visco-plastic, which means that, especially at higher moisture contents, the slope of the measured stress–strain curves depends on the strain rate. The apparent modulus (slope of the stress–strain curve) increases if strain rate is increased. At moisture contents of 50% or higher, it is governed by interactions between fibers that are mediated by liquid water. Therefore, any stress created by constrained deformations would rapidly relax to zero. In addition to elastic modulus, the softening effect of moisture is evident in the stress–strain behavior of paper, discussed next.

Observation 8

It is in interest of this study to find the possibility to use paper products as a structural elements in architecture. As these should have properties as stable as possible, it is essential to find the way to stabilize paper structure against humidity.

Some ideas are given in chapter 6.

4.2 **Stress–strain behavior of paper**

Studying and comparing diverse sources, the most complete explanation of stress-strain behavior of paper is found in Mechanics of Paper Products [31]. Here are extracted some essentials of interest, which will serve as background on a further arguments of this research. For complete information, consult the source.

4.2.1 In-plane tensile loading

In principle, a stress increment may cause an instant or delayed and reversible (i.e., elastic) or irreversible (i.e., inelastic or plastic) strain increment Fig. [IV / 14]. The presence of a delayed response implies that the stress–strain behavior is time-dependent or rate-dependent. Furthermore, the relationship between stress and strain can be linear or nonlinear. The stress–strain curve of paper exhibits all these behaviors. The time-dependence seen in the creep and stress relaxation of paper is discussed in Chapter 5. This section gives a general overview of the different aspects of the three-dimensional stress–strain behavior of paper.

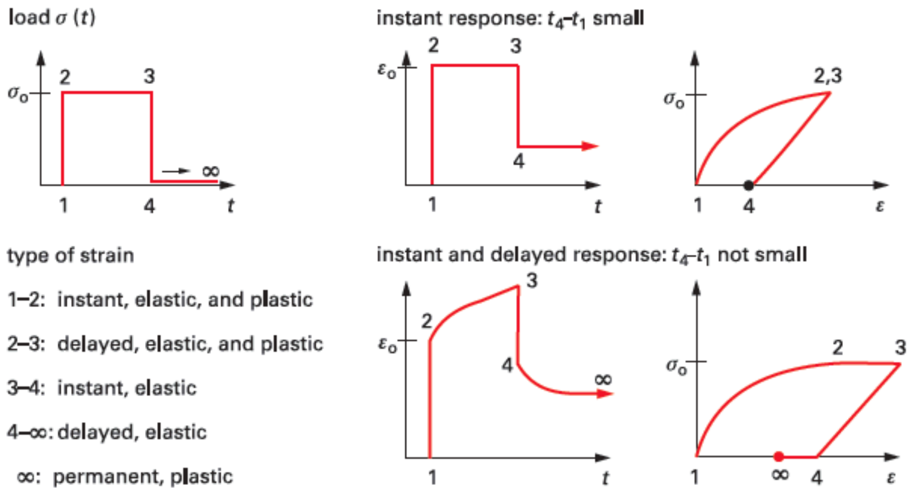


Fig. [IV / 14] - Instant and delayed response to load. [31]

A recursive tensile in-plane stress–strain measurement of paper usually gives a result of the type shown in Fig. [IV / 15]. One can see that the elastic modulus changes very little even though part of the strain is irreversible or plastic. This is typical of almost all paper grades: the elastic modulus decreases by a maximum of 10% before the breaking point is reached. Brittle paper grades, such as baking paper or glassine, exhibit a larger loss in the elastic modulus, while ductile paper grades, such as sack paper, show a modest increase. Corresponding stress–strain curves are illustrated in Fig. [IV / 16].

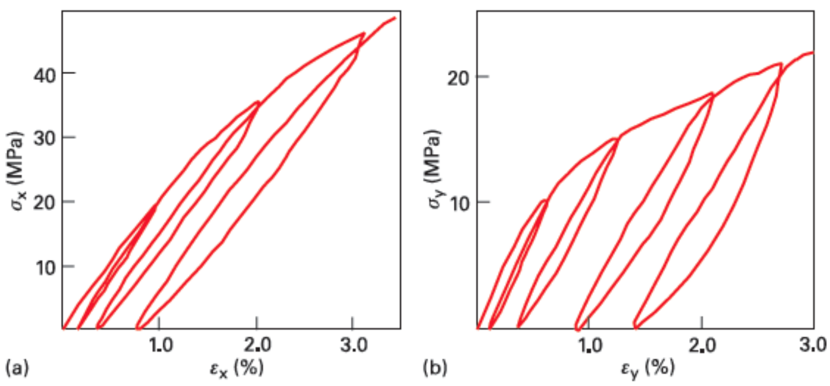


Fig. [IV / 15] - Recursive stress–strain curves of a paperboard in MD (a) and CD (b), from Persson (1991). [31]

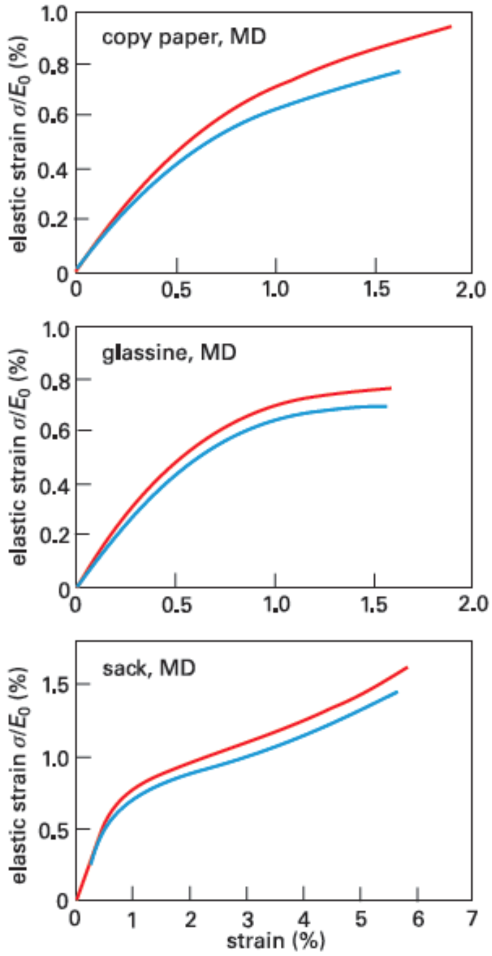


Fig. [IV / 16] - Examples of MD stress–strain curves of some machine-made paper grades. Stress values are divided by the elastic modulus E0 measured initially at zero strain, giving an estimate of the elastic strain. Data courtesy of Lauri Salminen. [31]

The fact that the elastic modulus of paper changes only a little before the peak stress suggests that the microscopic fibers' network structure undergoes permanent plastic deformations that do not weaken elastic stiffness of the fibers. However, after the peak stress the elastic modulus decreases. This is apparent in the post-peak unloading–reloading cycles shown in Figure [IV / 17]. The post-peak behavior in general can be recorded only when short specimens are used; long specimens show sudden failure at the peak stress.

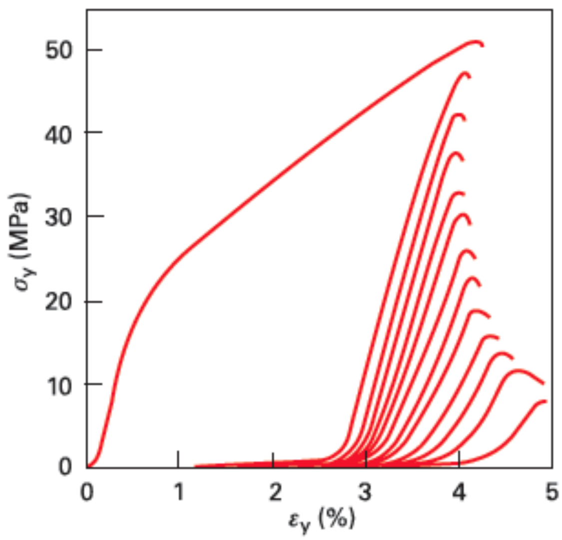


Fig. [IV / 17] - Post-peak reloading stress–strain behavior of paperboard in CD using 5 mm long and 15 mm wide specimens. [31]

4.2.2 Visco-elastic effects

The softening effect of moisture is shown in Fig. [IV / 18]. The elastic modulus and breaking stress are lower and the breaking strain is higher at the higher relative humidity, corresponding to the higher moisture content in the paper.

In the in-plane tensile stress–strain curves displayed in Figs. [IV / 16] and [IV / 18], the breaking strain of paper ranges from 1%–5%, which is quite typical. The values increase with increasing moisture content, and they may decrease with increasing strain rate. The breaking strain of paper falls below 1% only in very special cases. One can also see that the apparently linear part of the curves ends somewhere in the neighborhood of 0.5%. The breaking stress is usually strongly correlated with the elastic modulus so that the ratio of the two is close to 1%, and the in-plane tensile breaking stress values range from 10–100 MPa.

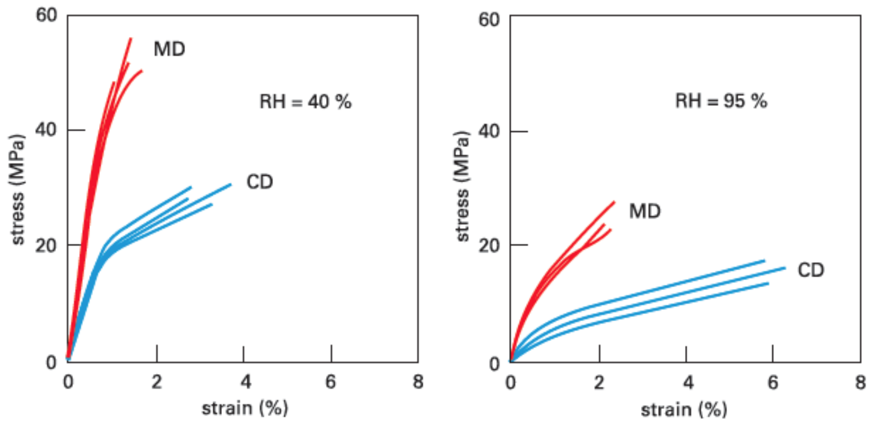


Fig. [IV / 18] - Stress–strain curves in MD and CD of a paperboard at relative humidity of 40% and 95%. The corresponding moisture contents are 6.6% and 20%. Drawn using data of Yeh, Considine and Suhling (1991). [31]

4.2.3 In-plane compressive loading and multi-axial strength

Because paper is a thin planar material, the measurement of in-plane compression is complicated. Buckling of the specimen must be prevented with some fixture that creates in-plane forces. Even if buckling is prevented, paper fails under compressive stress much sooner than under tensile stress Fig. [IV / 18]. In the z-directional testing the situation is the opposite, and compressive behavior is easy to measure. The ZD compressive strain is determined by the pore volume fraction and surface roughness, which are both pressed away by the applied stress. As the pore volume closes, the apparent stiffness of the material increases rapidly toward infinity, giving an exponential compressive stress–strain curve in ZD.

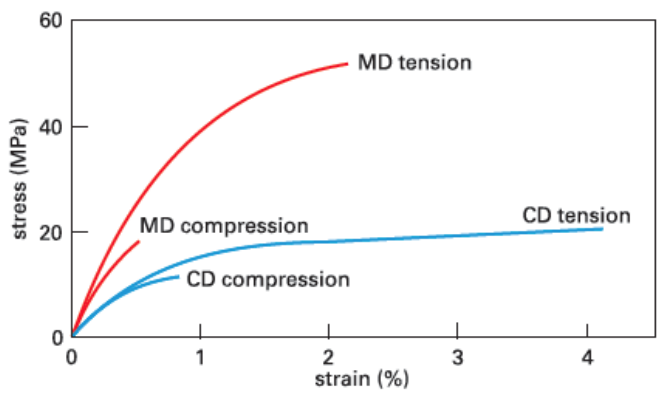


Fig. [IV / 18] - Comparison of compressive and tensile behavior of a paperboard in MD and CD, after Fellers (1980). [31]

In the Fig. [IV / 19] one can observe a much smaller area in the zone of compressive loading compared to the area of tensile loading.

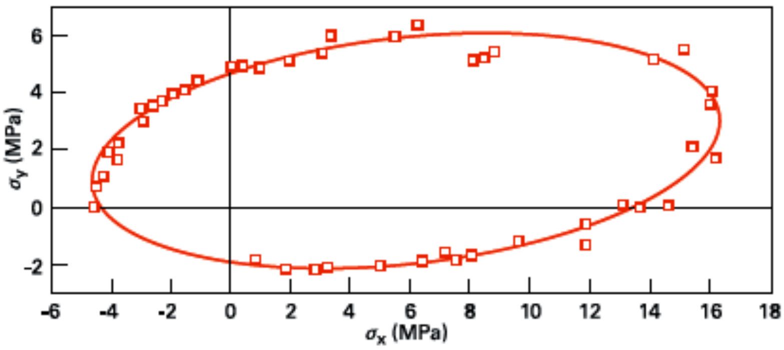


Fig. [IV / 19] - Biaxial strength data (squares) for a linerboard compared with the Tsai-Wu criterion (Eq. 2.8, line), after Fellers et al. (1983). Reproduced with permission from The Pulp and Paper Fundamental Research Society (www.ppfrs.org). [31]

4.2.4 Compressive failure

As demonstrated in Fig. [IV / 18], the compressive stress–strain behavior of paper is different from the tensile behavior. The compressive strength is only about 30% of the tensile strength. Compressive loading of a paper specimen to levels close to failure will not affect the strength obtained in a subsequent tensile test, whereas tensile loading to levels close to failure leads to a pronounced reduction in the compressive strength. Thus, the microscopic mechanisms of failure in compression are different from the mechanisms in tension.

The microscopic failure of paper in compression is caused by a structural instability (not rupture) of the fiber network. This happens through either the buckling of free fiber segments or the shear dislocations in fiber walls Fig. [IV / 20]. The first happens primarily in low density sheets, and the latter in medium and high density sheets. The microscopic buckling and shear dislocations in the fiber network change the distribution of compressive stresses. When compressive load is increased, more fiber segments buckle and shear dislocations increase until the whole sheet becomes structurally unstable. The macroscopic compressive failure is often associated with a shear slip dislocation that shows also delamination Fig. [IV / 21].

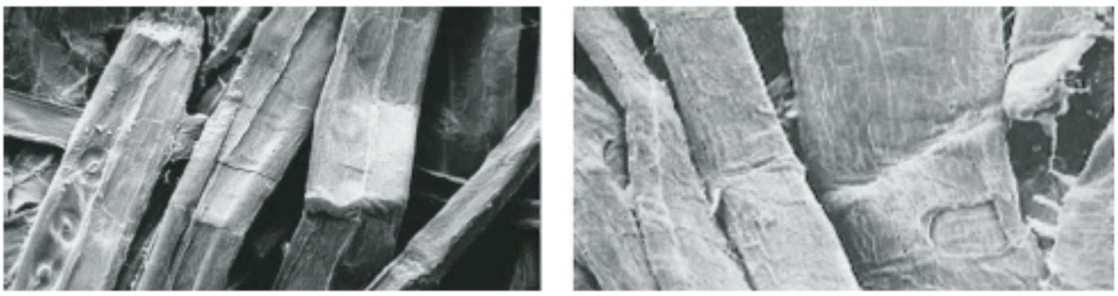


Fig. [IV / 20] - Microscopic compressive failures in paper: buckling of fiber segments (left) and shear dislocations in fiber walls (right). Courtesy of Christer Fellers. [31]

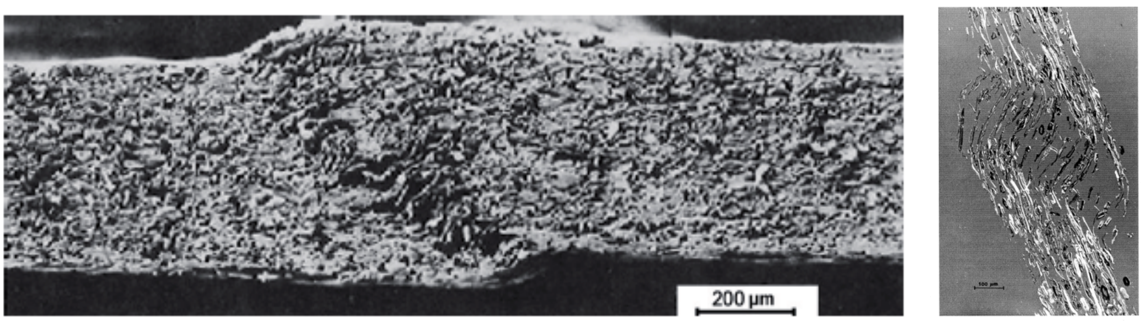


Fig. [IV / 21] - Shear band slip failure in compression, also showing delamination. Courtesy of Christer Fellers. [31]

The microscopic failure mechanism in compression explains why prior tensile loading affects compressive strength but prior compressive loading does not affect tensile strength. Inter-fiber bond failures in tensile loading increase the mean length of free fiber segments. As a result, the buckling threshold of fiber segments decreases. In the same way, if the creasing or folding of a carton board creates excessive delamination outside the fold area, then the compressive strength of a box decreases.

Observation 9

As mentioned in Observation 4.3, in order to waterproof paper product, other substance has to be applied and certain strategy should be chosen. In most cases found in architecture, protection is applied on surface, as a protective layer.

If the main reason of compressive failure is a buckling of fiber segments, maybe the strategy should contemplate a material small enough to enter the pores between segments, protect material against humidity intrinsically, and at the same time confine fiber segments in order to prevent their buckling. That way the behavior towards compressive loads would improve significantly.

4.3 **Stress–strain diagrams comparison**

One can understand necessity to compare diagrams from different sources, in order to obtain reliable data. Many mentioned factors (fibers, bonding, papermaking process...) may result in papers with different properties. Having in count the complexity of paper structure, no existing diagram will be completely reliable, except the one made on the proper material we want to use in construction. The typology of variables in paper structure requires constant load tests in production of structural elements.

Nevertheless, as a theoretical approach, it is useful to compare diagrams to obtain orders of magnitude. In the Fig. [IV / 22] is represented the selection of stress-strain diagrams from different sources, and in the Fig. [IV / 23] all those diagrams are scaled to the same proportions and overlapped.

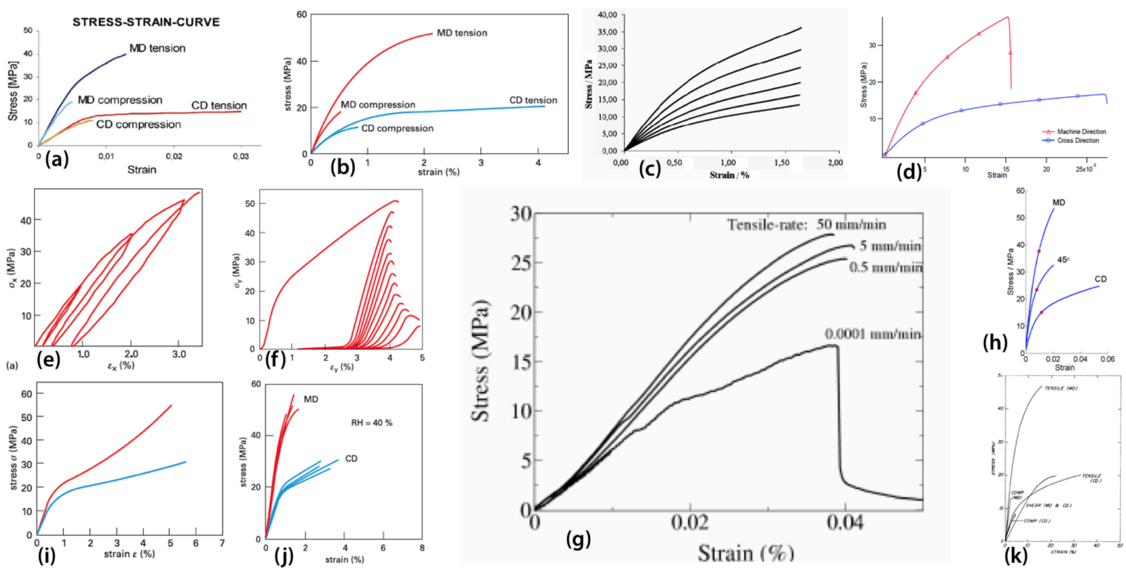


Fig. [IV / 22] - Stress-strain diagrams from different sources. (a) - [39]; (b) - [31]; (c) - [20]; (d) - [02]; (e), (f), (i), (j) - [31]; (g) - [40]; (h) ; (k) - [36].

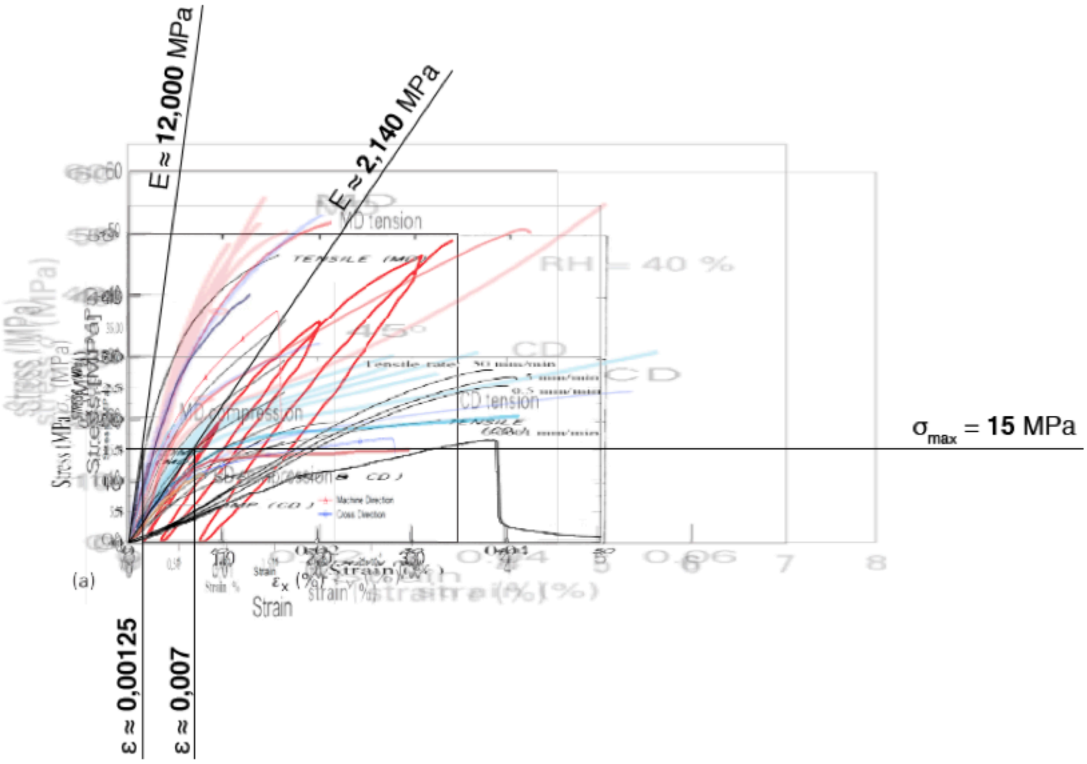


Fig. [IV / 23] - Scaled and overlapped diagrams from Fig. [IV / 22]. Elaborated by the author.

Observation 10

In almost all diagrams one can see that tensile strength in MD is between 40 and 60 MPa. However, no one of these diagrams contemplates the time factor. There is only one diagram which applies different tensile rates, and that one reveals some interesting informations.

What explains the diagram, is that there is notable difference in maximum strength of material if we load the sample fast or slowly. Slower the tensile rate, lower the maximum strength.

If material is intended for a structural use on a long term basis, then this behavior is very important. The conclusion of the experiment is that, as slow as we load the sample (even eternally loaded), if we do not get over 16 MPa in tensile stress, the material will never break.

Hence, it is possible now to put some approximate numbers read from diagrams.

The density of Linerboard is **ρ**=691 kg/m^3. Elastic modulus E is between 2,140 MPa -12,000 MPa. If we put the tensile limit for long term structural use around 15 MPa, elastic strain **ε** would be between 1,25 ‰ - 7 ‰.

These numbers are only rough orientation, but enough to continue the insight.

5. Long-term mechanical properties

5.1 **Creep and relaxation as phenomena**

Creep and relaxation are the two customary phenomena associated with time-dependent behavior. They are opposite manifestations of the dissipation of energy from a material under some state of stress. The definitions are as follows:

– Creep: The increase in strain **ε** (t) over time under a constant state of stress, **σ** = constant, t ≥ 0.

– Relaxation: The decrease in stress **σ** (t) over time under a constant state of strain, **ε** = constant, t ≥ 0.

The creep and relaxation are a result of redistribution of stresses at some length scale in the material. These could be molecular, micro-, or macro-level redistributions. Here we treat the phenomena as being valid as a continuum and ignore what leads to them.

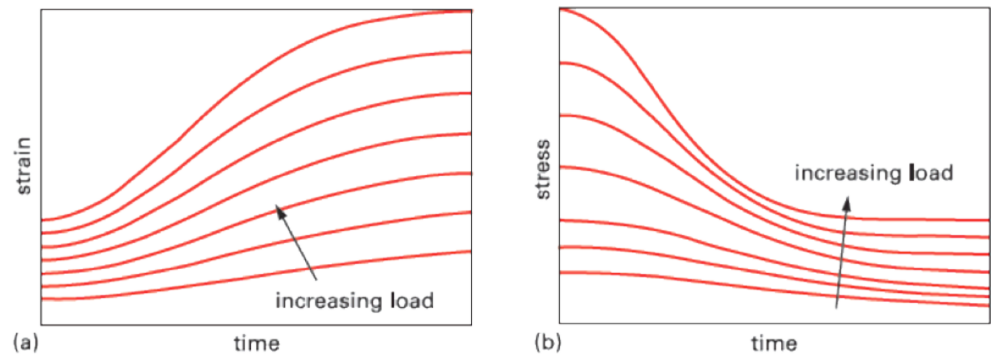


Fig. [V / 1] - Family of creep curves (a) and stress relaxation curves (b). [31]

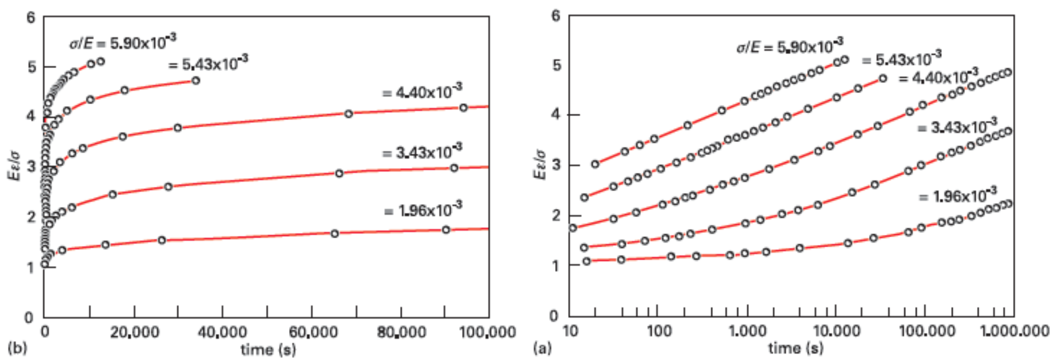


Fig. [V / 2] - Representation of the data of Brezinski (1956) as the product of the initial modulus and creep compliance for logarithmic time scale (a) and linear time scale, but for a shorter time range (b). [31]

The important observations are as follows:

1. The rate of creep decays with time (exponential decay in the rate of creep).

2. Increased load results in disproportionately larger creep compliance (nonlinearity).

3. At high loads or long times, the rate of change in creep compliance is constant when expressed with respect to logarithmic time.

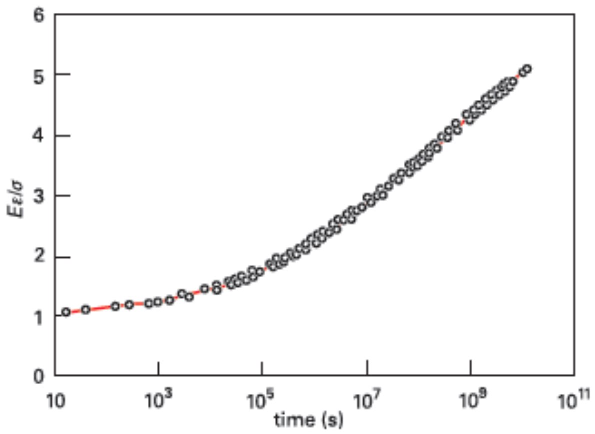


Fig. [V / 3] Master curve of creep formed by moving the curves in Fig. [V / 2] (a) parallel to the time axis. [31]

Observation 11

Measuring creep and stress relaxation curves, one can make the first approximation of relation between the instant elastic strain and creep strain, as well as between the instant stress and final stress over time.

As mentioned, increased load results in disproportionately larger creep compliance (nonlinearity), but the relation between instant strain and creep strain remains the same.

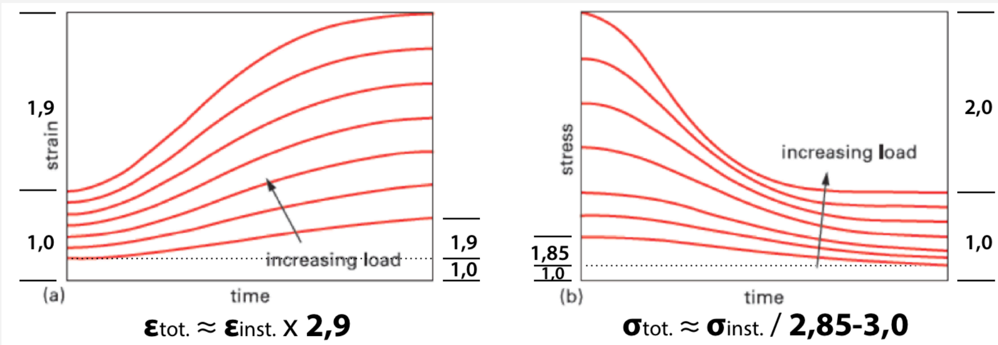


Fig. [V / 4] - Relations between instant elastic strain and creep strain (a) and instant stress and final stress over time (b). Edited by the author.

Fig. [V / 5] - Graphical interpretation of creep and relaxation phenomena. Elaborated by the author.

Investigation of Almut Pohl [36] brings precise explanation of creep and relaxation phenomena:

"(...) Both creep and relaxation phenomena can be observed in paper. Creep in particular is important for all structural uses of paper. When a permanent load is applied, the strain in the material increases rapidly at first.

This nonlinear steep rise is followed by a long period of linear increase in strain over time. Depending on the loading level, this period is followed more or less quickly by a very rapid increase of strain over time and *subsequent failure. These three distinct sections of the creep curve are called primary, secondary and tertiary creep Fig. [V / 6]. At a low stress the material may not enter the phase of tertiary creep during its lifetime.*

Creep and relaxation rates are affected by the magnitude of the applied load and by moisture. Under large loads and in high ambient humidity environments creep and relaxation rates are higher. Changing relative humidity levels (from high humidity to low humidity and back) generally induce higher creep and relaxation rates than a constant high humidity environment.

Creep and relaxation effects of paper are partially due to the viscoelastic properties of the paper components themselves. They are aggravated by the rupture of some fibre-to-fibre bonds due to a localized stress or to moisture and subsequent sliding of the fibrils relative to each other.

Paper can exhibit large creep deformations. In standard conditions, a long application of only small loads can induce very high strains in paper." [36]

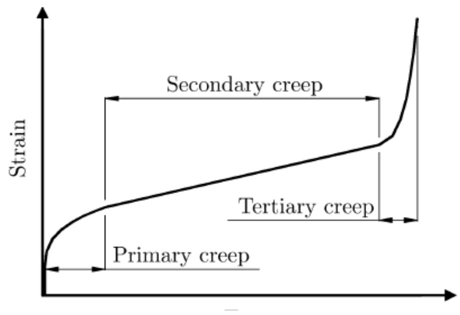


Fig. [V / 6] General shape of the creep curve of paper. [36]

Observation 12

Primary creep is very short in time Fig. [V / 8], and it will be considered here as inseparable part of instant strain. Measuring relations in this graphic, one can see that relation between the instant and creep strain is similar to one measured in Fig. [V / 4] (3,15 vs 2,9).

What is interesting is that almost 50 % of total strain is tertiary creep. If we maintain material at low stress and it never enters tertiary creep, than, in order to calculate the structure, the creep strain would be significantly reduced.

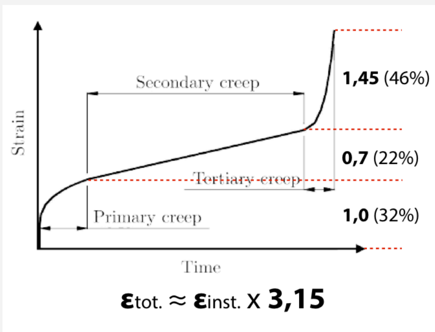


Fig. [V / 7] Relation between distinct sections of the creep. Edited by the author.

In the research of Schönwälder, Zijl and Rots [40], tensile creep of cardboard is studied. In their study, previous theoretical explanation of creep phenomenon can be recognized in a practical test.

The measured creep responses are presented in Fig. [V / 8]. For stress levels up to roughly half the tensile strength (in this case 26 MPa) both primary and secondary creep at sustained uniaxial tensile loads can be distinguished and no failure occurs. Beyond this range, tertiary creep also occurs, leading to failure of the specimen at the sustained load.

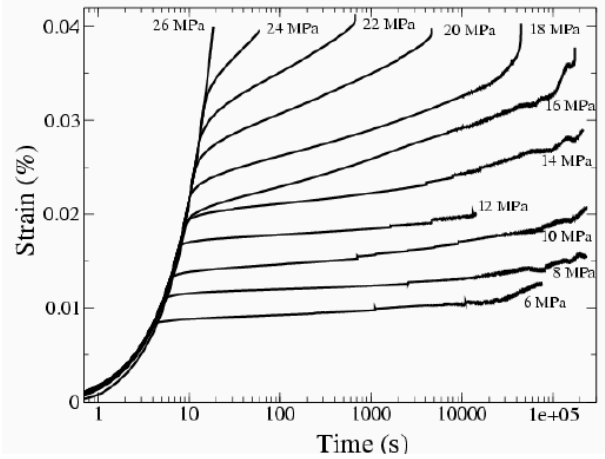
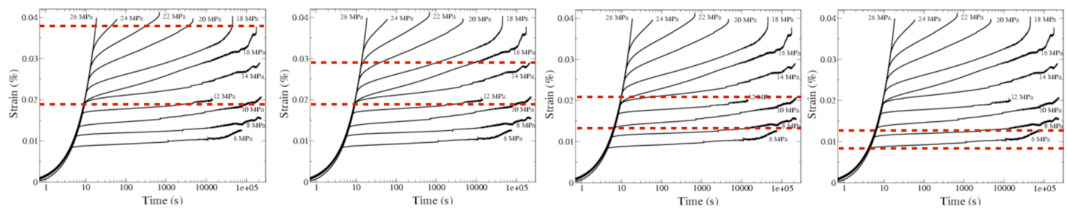


Fig. [V / 8] - Experimental Tensile creep response at various sustained load levels. [40]

Observation 13

Comparing relations between instant and creep strain for different stresses, one can observe important creep increase between 14 MPa and 16 MPa stresses (1,52 vs 1,95). Stresses below 14 MPa maintain more or less the same creep proportion, around 1,50-1,60 times instant strain.

Stress of 16 MPa is the limit where starts to appear delayed fracture (after tertiary creep). Therefore, this stress could be considered as maximum stress for a long term structures. Considering similar creep proportions, stress of 14 MPa could be considered as a admissible stress for a long term structures.



$\sigma(t) = \mathbf{16}$ MPa
$\varepsilon_{inst.} = \mathbf{1{,}90}$ %
$\varepsilon_{inst.} : \varepsilon_{dif.} = \mathbf{1: 0{,}95}$
$\varepsilon_{tot.} \approx \varepsilon_{inst.} \times \mathbf{1{,}95}$

$\sigma(t) = \mathbf{14}$ MPa
$\varepsilon_{inst.} = \mathbf{1{,}90}$ %
$\varepsilon_{inst.} : \varepsilon_{dif.} = \mathbf{1: 0{,}52}$
$\varepsilon_{tot.} \approx \varepsilon_{inst.} \times \mathbf{1{,}52}$

$\sigma(t) = \mathbf{10}$ MPa
$\varepsilon_{inst.} = \mathbf{1{,}35}$ %
$\varepsilon_{inst.} : \varepsilon_{dif.} = \mathbf{1: 0{,}56}$
$\varepsilon_{tot.} \approx \varepsilon_{inst.} \times \mathbf{1{,}56}$

$\sigma(t) = \mathbf{6}$ MPa
$\varepsilon_{inst.} = \mathbf{0{,}85}$ %
$\varepsilon_{inst.} : \varepsilon_{dif.} = \mathbf{1: 0{,}51}$
$\varepsilon_{tot.} \approx \varepsilon_{inst.} \times \mathbf{1{,}51}$

$$\sigma_{max.}(t) = \mathbf{16}\ \text{MPa}$$
$$\sigma_{adm.}(t) = \mathbf{14}\ \text{MPa}$$
$$\varepsilon_{tot.} \approx \varepsilon_{inst.} \times \mathbf{1{,}5\text{-}2{,}0}$$

Fig. [V / 9] Relations between instant and creep strain for different stresses. Elaborated by the author.

Another important detail is the difference between instant stress and final stress under the same strain. In Fig. [V / 4] one can see that final stress is around 3 times lower than instant stress.

Phenomenon of relaxation can be useful for pretreating the material. If we put a sample under a strain which produces stress of 14 MPa, after the period of relaxation, the final stress over time would be around 4,7 MPa, which gives a difference of 9,3 MPa. If the sample does not deform additionally, this relaxed stress will remain stored and unused in the material.

It would be interesting to consider prestressing of paper until completely relaxed, before using it as a structural element, in order to use its maximum stress capacity.

5.2 **Stress transmission**

In Mechanics of Paper Products [31] is explained what happens inside the paper when loaded:

"*(...) Our discussion of the stress–strain and creep behavior of paper is consequently limited to qualitative observations of the behavior of fiber segments. We start by considering what happens if the simple fiber segment in Fig. [V / 10] (a) is strained. At small strains, the whole segment (including the bonded ends) elongates elastically. Then at some point, the local stress at the "bond corners" A and B exceeds some limit value, and the bond starts to open there. The opening process continues if the elongation is further increased and may eventually result in the situation shown in Fig. [V / 10] (b). The onset of the gradual bond opening process must depend on the activation of the fiber segment. In an inactive segment, any "slack" in the free segment part (between points A and B) must first be stretched out before bond opening can begin.*" [31]

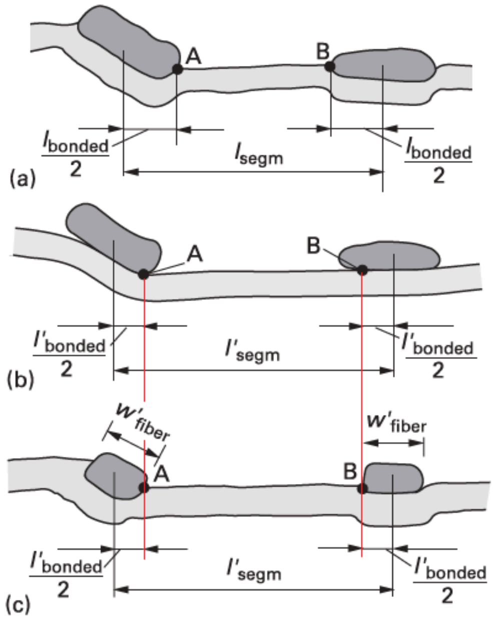
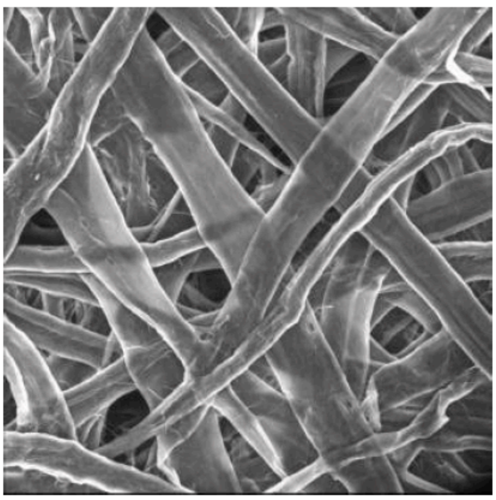


Fig. [V / 10] - Schematic drawing of the bond opening process. When the segment in (a) is strained, gradual bond opening leads to the situation in (b). The bonded segment length has decreased to l'_{bonded} and the free segment length increased to $l_{segm} - l'_{bonded}$. The same length values could also have been achieved without straining if the fiber width were smaller and segment length larger in the first place, $w'_{fiber} < w_{fiber}$ and $l'_{segm} > l_{segm}$ (c). [31]



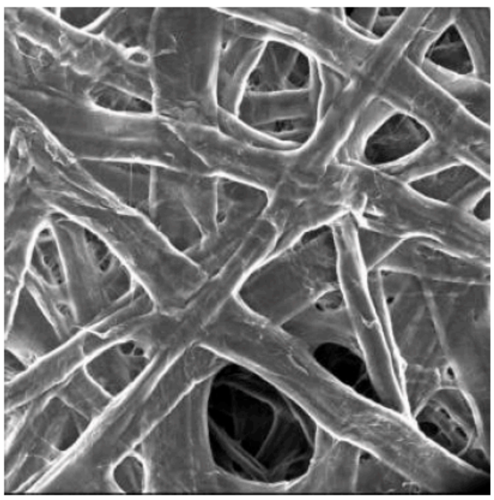


Fig. [V / 11] - Scanning Electron Microscope image of a paper surface (KCL). Two cases, paper dried under tension (left) and free of tension (right), are shown. The difference between active and inactive segments can be seen.

Observation 14

After this insight, we can clearly understand the creep phenomenon's mechanism. Once the paper product is loaded, the stress transmission will flow through the activated segments, creating high tensions in bonds. Bond opening process will free a part of active segment, which will result in its lengthening. This prolongation of active segments will make other segments to stretch and become active. After bond opening process, the tensions will be redistributed until enough active segments share uniformly stresses and maintain bearable tensions. The creep of structural element is a result of all these bond openings and stresses micro-redistributions.

As mentioned in Observation 5.3, pre-stressing could improve behavior of structural element. The objective of pre-stressing is to activate all fiber segments, so once the element is loaded, the stress would be uniformly distributed between all its fibers. That way the creep phenomenon could be almost completely avoided.

Summary on Part 2

Some mechanisms that control the mechanical properties of paper were described in this chapter.

Mechanical properties of paper depend primarily on two mechanisms that act during the papermaking process:

1. Network densification in pressing that controls inter-fiber bonding, fiber segment lengths, and geometric deformations such as fiber twist; and

2. Fiber segment activation that controls the elastic modulus of fiber segments, as well as their stress–strain behavior and hygroexpansivity, which are strongly influenced by the bonding with other fibers.

In order to determine relevant mechanical properties of fibers and inter-fiber bonds, one should not rely completely on experiments done on single fibers or inter-fiber bonds. It is very difficult to reproduce the conditions that prevail in the fiber network during the papermaking process. More reasonable approach is to measure paper properties and then deduce the fiber and bond properties from macroscopic results.

As mentioned in chapter 4.3, due to random and complex paper structure, highly influenced by papermaking process, it is necessary to make load tests constantly while producing structural elements, in order to infer precise mechanical properties.

Roughly, one can consider some theoretical limits and range properties of Linerboard intended for a long term structural use, deduced from relevant experiments and previous research.

Linerbord mechanical properties for a long term structural use:

$\boldsymbol{\rho}$ = **691** kg/m^3

E = **2,140** MPa - **12,000** MPa

$\boldsymbol{\sigma}_{max}$ instant = **40**-**60** MPa

$\boldsymbol{\sigma}_{max}(\Delta t)$ = **16** MPa

$\boldsymbol{\sigma}_{adm}(\Delta t)$ = **14** MPa

$\boldsymbol{\varepsilon}_{elastic\ (max.\ 14\ MPa)}$ = **1‰** - **7‰**

$\boldsymbol{\varepsilon}_{tot.} = \boldsymbol{\varepsilon}_{inst.}$ x **1,5** - **2,0**

Part 3

6. Interventions of interest in linerboard

The softening effect the moisture has on paper is explained in chapter 4.2.2. As mentioned in Observation 4.3 without any protection of paper product, it is not possible to count on it as a long term structural material because of its high sensibility and loss of mechanical properties in humid environments.

The intervention, concerning improvement of behavior in humid environments, needs a certain strategy counting on the function of the final product. Most probably, the intervention will imply another material which can compensate the weak points of the principle one, and as a combination, the new obtained material should have elevated mechanical properties.

Extending the property range of paper products is studied in wood composites, which is the first approximation to existing products and their properties. In observation afterwards (6.1) will be discussed the most important properties to improve, and the theoretical intervention strategy.

6.1 **Wood composites**

The forest products industry relies heavily on paper, paperboard, and sawn timber, but also on a category of established products sometimes classified as "traditional wood composites": glulam, plywood, particleboard, fiber board, and so forth. It is helpful to consider paper and paperboard products in the same context as wood composites because this puts a stronger emphasis on the engineering materials nature of load-bearing materials. Traditional wood composites are often used in the building industry, where many structures are subjected to significant loads, which can be both static and dynamic.

A widening of the perspective for wood fiber-based materials by inclusion of composite materials is of great interest because it may help to find new applications in large material volume areas such as the building, automotive, and packaging industries. Also, a context of composite materials rather than forest products is helpful because the science and engineering of materials puts a strong focus on the micro-scale structural organization of material constituents. Focus is on the relationships between processing and microstructure, and between microstructure and properties. Material components such as fibers and polymers are subjected to processing and combined into a material with a certain microstructure. During processing, the material is also given geometrical shape. Common examples in the context of structural mechanics include plates, beams, and cylinders. A material of a given shape can then serve simple or complex functions, such as transmitting loads, heat, and the ability to survive repeated folding or storing energy at minimum weight.

The term composite material does not have a unified definition accepted over all different categories of composites, but the following criteria have been presented:

1. A composite material consists of two or more physically distinct and separable material components (constituents). Usually, the properties of different constituents are substantially different.

2. In order to optimize the properties, the composite can be prepared by mixing the constituents so that the structure, to some extent, can be controlled.

3. The properties are superior, and possibly unique, compared with properties of individual constituents.

Common constituents that can offer substantial potential for mechanical reinforcement include fibers, platelets, particles, and ribbons (i.e., fibers that have a rectangular cross-section and substantially larger width than thickness). Air is also a constituent so that foams and porous networks (paper, fiberboard) can be classified as composites.

Table [VI / 1] presents some examples of current material categories that can be classified as wood composites. We have made the classification according to the micro-structural characteristics and the scales of constituent size or constituent type. Some application examples are also presented.

Wood composite category	Specific wood composite material	Description	Example of applications
Polymer-modified wood	Impreg	Wood is impregnated by monomers, which are polymerized.	Flooring
Laminated wood	Plywood	Veneer layers are laminated and bonded with a certain veneer orientation distribution.	Building industry, furniture
	Laminated veneer lumber (LVL)	Veneer layers are stacked to form laminated beams.	High-strength beams for building industry
	Glulam	Board layers are stacked to form beams.	Beams for building industry
Strands or particles with adhesive	Particle board	Large wood particles are coated by adhesive and hot-pressed to porous particleboard.	Furniture, building industry
	Oriented strand board (OSB)	Anisotropic strands are coated by adhesive and compressed to oriented high-density boards.	Competes with plywood at lower cost
Porous wood fiber networks	High density fiberboard (HDF) (850–1100 kg/m^3)	Mechanical or Masonite pulps are hot-pressed and bonded by lignin or adhesive.	Flooring, siding, wall panels, furniture
	Medium density fiberboard (MDF) (600–800 kg/m^3)	Mechanical pulp is combined with an adhesive and hot-pressed.	Furniture, cupboards, doors flooring
	Paper (kraft paper 600–800 kg/m^3)	Wood pulp is filtrated and dried into network.	Printing, packaging
	Paperboard	Typically thicker than about 0.25 mm (ISO definition: >224g/m^2).	Packaging
Impregnated wood fiber networks	Paper laminates	Paper is impregnated by resin and polymerized.	Electric insulation boards, flooring
Short, discrete wood fibers in polymer matrix	Wood plastics	Saw dust or wood pulp is mixed with thermoplastic or resin and is extruded, injection molded, or foamed.	Decking, building industry, furniture, automotive

Tab. [VI / 1] - Material categories that may be classified as wood composites. [31]

Wood composite	Density (kg/m^3)	Elastic modulus (GPa)	Bending strength (MPa)	Tensile strength (MPa)
Spruce board	400	11	9.3	n.a
Spruce glulam	400	12.4	16.6	n.a
Spruce LVL	≈550	14	51	42
Spruce plywood	≈550	6.9–13	21–48	6.9–13
Oriented strand board (OSB)	≈550	4.8–8.3	21–28	6.9–10.3
High-density fiberboard (HDF)	850–1100	2.8–5.5	31	15
Medium-density fiberboard (MDF)	600–800	2	20	n.a
Particleboard	550–750	2–4 (from bending)	15–25	n.a
Kraft linerboard	600–800	2.8–4.1	n.a	25 (4% failure strain)
40wt% wood fiber/ PP and MA-PP	1030	4.2	n.a	52 (3.2% failure strain)
Nanopaper	1300	13	n.a	200–300 (10% failure strain)

Tab. [VI / 2] - Typical densities and mechanical properties of different wood composite materials. [31]

The orientation distribution of the reinforcement component as well as its size is important for the mechanical properties of the composite. Larger constituents tend to result in materials with larger defect size and, therefore, lower strength. Oriented reinforcement provides higher strength in the orientation direction, and this is one of the main advantages of composite materials. It makes it possible to tailor the anisotropy (orientation dependency) of the material properties.

The typical densities and mechanical properties of different wood composites are listed in Table [VI / 2]. Density is important to consider in material comparisons because mechanical properties show strong dependency on density. Because wood composites tend to be porous, the correct parameter in a micro-mechanics context is the relative density or volume fraction, as will be discussed later.

Comparing the different materials in Table [VI / 2], spruce wood has good mechanical properties but is limited by the restricted geometric shape. Complex machining operations are required. The anisotropy and high porosity also results in locally weak regions in machined structures of complex shape. Laminated structures such as LVL beams and plywood sheets often show high strength due to the thin lamellae. In addition, the orientation distribution of the lamellae can be controlled. Again, there is little freedom with respect to shape. The comparison between high-density fiberboard and a linerboard is of some interest. Kraft linerboard is a paperboard made of chemical pulp fibers and used as the surface ply in corrugated boards. It has higher strength than the fiberboard, despite lower density. The wood fiber/polypropylene composite (an example of wood plastics) is also interesting. This material category is very successful in North America for decking applications, replacing impregnated wooden boards. It can also be injection molded into complex geometrical shapes. The elastic modulus is quite high, and the strength is respectable compared with many other materials. The main structural advantage of wood plastics is low porosity. This is interesting because it indicates the potential of new types of composites based on wood fibers.

The wood fiber itself has attractive characteristics including high aspect ratio (the length-to-diameter ratio), high axial strength and elastic modulus in the fiber wall, as well as favorable fiber network forming characteristics. Networks made of strong wood fibers or chemically tailored fibers can be used in new fiber architectures of designed orientation distributions and combined with new polymer matrices, foams, or other porous materials to form new types of wood composites. Interesting functions include thermal insulation and mechanical performance. Wood fiber composites could also provide new opportunities with respect to molding of intricate geometrical shapes. The “nanopaper” material in Table [VI / 2] represents some of the advantages that can be obtained with cellulosic nano-fibers. Their dimensions are three orders of magnitude smaller than regular wood fibers. The elastic modulus is 13 GPa, and the strength in tension exceeds 200 MPa due to the fine structure of the material.

The development of new wood composites should preferably be motivated by new applications for wood-based materials. Property comparisons with other categories of materials will then be helpful and can be pedagogically made by the use of so called property charts, such as Figure [IV / 10].

Observation 15

The objective of this work is to understand micro-mechanisms of paper products and to see if it is possible, in a optimum manner, to convert them into durable load-bearing structural elements for architectural use.

This imply not only protection in humid environments, but an intervention strategy which would improve also long-term mechanical properties and behavior, as a creep strain and stress resistance. Deducing from previous research, there are five important fields to count on in intervention:

1. Intrinsic waterproofing of material
2. Fiber segments activation (creep reduction)
3. Increasing of compression resistance
4. Initial and final stress difference (relaxation)
5. Experimental determination of mechanical properties

The fields 1-4 should be influenced directly creating composite material, while the fifth point only reminds on the impossibility to determine mechanical properties theoretically. Despite this difficulty, it is interesting to develop theoretical intervention strategy, which could help architects in orientation of their experimental work.

6.2 **Intervention strategy**

Paper products behavior is determined by the properties of internal cellulose fibers network, which was studied previously. In order to establish right intervention strategy, one can make a hypothetic case of a structural element made of paper, analyzing it step by step, observing the combination of creep and relaxation phenomena together.

Simplifying, we could imagine our paper product as a sample of three fibers[1] with viscoelastic behavior, each one with different length Fig. [VI / 3]. Once we load the sample, the 100% of stress would be supported by the shortest fiber (1). By the weight of the load, this fiber would extend, until the next shortest fiber enters into load (2). The stress would start to redistribute, until both of fibers share it equally. The same would happen until the third fiber starts to be active. Finally, after a certain period, the fibers would redistribute equally the stress, and the first one, which supported 100% of the stress in the beginning, at the end would support 33%. That means, that by the pass of time, it would relax.

The result of these strains and tensional redistributions, the difference between the step (1) and (3), is the creep strain ($f_{dif.}$).

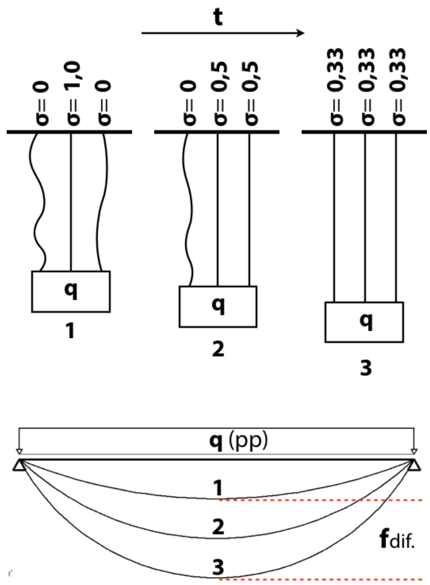


Fig. [VI / 3] - Simplified explanation of creep and relaxation phenomena (viscoelastic period). Elaborated by the author.

Once the stress is equally distributed between the fibers, we could say that the sample would start entering elastic behavior. In reality, the behavior probably would not be completely elastic because the bond opening process would continue until failure. Nevertheless, we could consider that all the stresses would be equally distributed, which means that new bond openings would be reduced to the minimum and macroscopic behavior of element would be elastic.

In “elastic” period, Fig. [VI / 4], if we load the sample additionally, all the fibers would receive the equal part of stress, which would produce additional strain to the sample (2). Now, if this stress does not overcome the long-term admissible limit (14 MPa), the uniformly distributed stress would not produce any new bond openings, which means that once we unload the sample, it would return to its initial position as a consequence of the elasticity of the fibers. In theory, the creep and relaxation phenomena would not be present, so we could consider this period as a “elastic period”.

1 The reason for election of three fibers as an example is a deduction from relaxation diagram in the observation 5.1, where the initial stress is around three times bigger than the final stress.

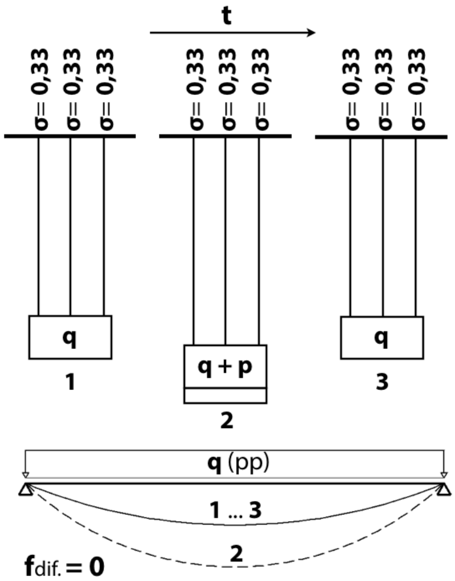


Fig. [VI / 4] – "Elastic period". Elaborated by the author.

For a design of durable load-bearing structural elements, it is more interesting to count on elastic than viscoelastic material, for easier control of deformations.

Therefore, the starting point of intervention strategy is how to pre-stress linerboard in order to achieve its "elastic period"?

The total strain in linerboard is a mixture of elastic and creep strain Fig. [VI / 5]. In order to prepare material for its "elastic period", it is necessary to apply stress over time, until all process of uniform stress distribution is finished. After that period, when we unload the material, it will shrink equally to its elastic strain. Then we could consider it at the beginning of "elastic period".

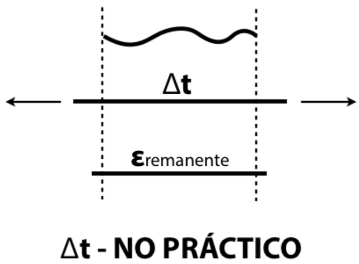


Fig. [VI / 5] - Mixture of elastic and creep strain. Elaborated by the author.

If we consider the time variable as unknown (even though we can deduce it from Fig. [V / 8], then it would not be very practical to maintain all the unknown necessary time the material under stress. Instead of maintaining the material under stress, we could capture its elastic energy and transmit it in form of compression to the capturing element Fig. [VI / 6]. Afterwards, this compression would induce a creep strain to the linerboard. Over time, the linerboard would be completely relaxed (which means, all of its fiber segments activated), i.e. at the beginning of "elastic period".

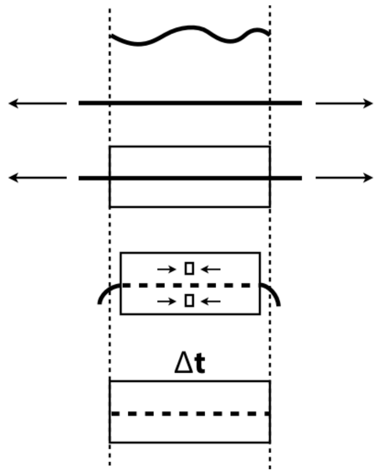


Fig. [VI / 6] - Pre-stressing model by compression capturing. Elaborated by the author.

If we try to put numbers in this model, considering the relaxation and long-term admissible stress, then we would obtain finally a pre-stressed element as shown in Fig. [VI / 7].

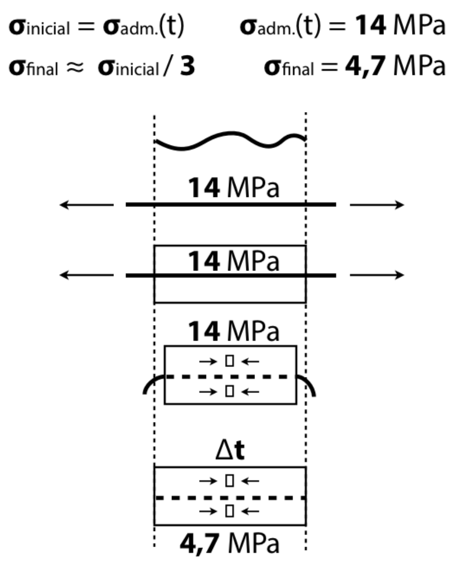


Fig. [VI / 7] - Obtention of the pre-stressed element. Elaborated by the author.

The next question is which material is suitable enough to capture the compression and improve linerboard's weak points?

The very small thickness of linerboard and even smaller size of pores within its fiber network, require a material with particles small enough to penetrate inside, confine fiber segments and absorb compression. The first association of a material with these characteristics is cement. The Fig. [VI / 8] is a schematic representation of cement particles related to the cellulose fibers.

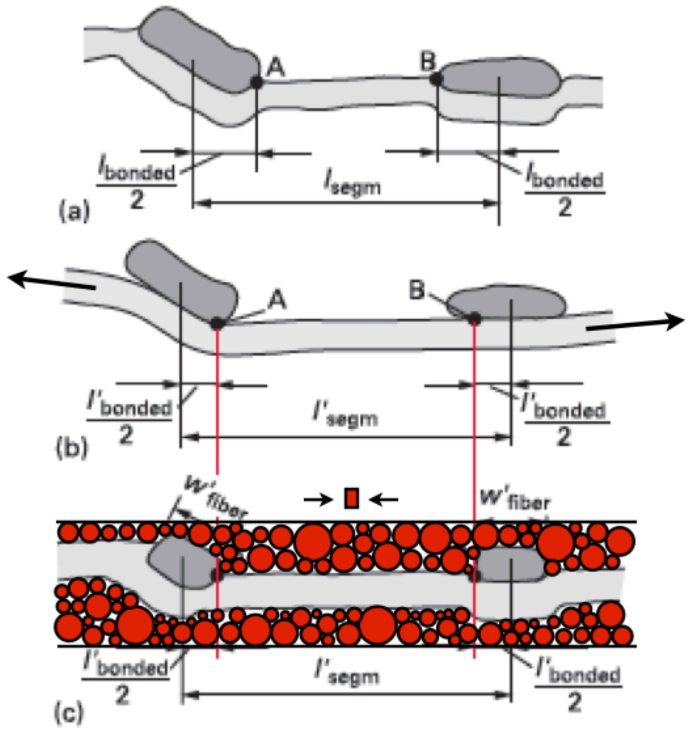


Fig. [VI / 8] - Schematic representation of cement particles related to cellulose fibers. Edited by the author.

Thanks to the dissertation of Almut Pohl [36], and her conclusions about optimum combination of cement and cardboard, one can see the clear cement penetration between cellulose fibers Fig. [VI / 9] and [VI / 10]. Although, as explained previously, cement impregnation of existing paper products, without pre-stressing them, will result in a structural element with viscoelastic behavior under tension.

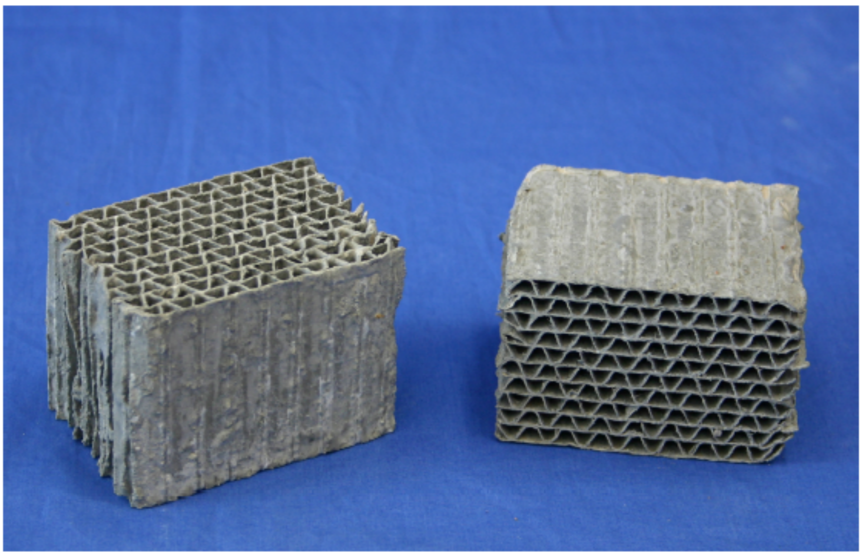


Fig. [VI / 9] - Samples of cement impregnated honeycomb. [36]

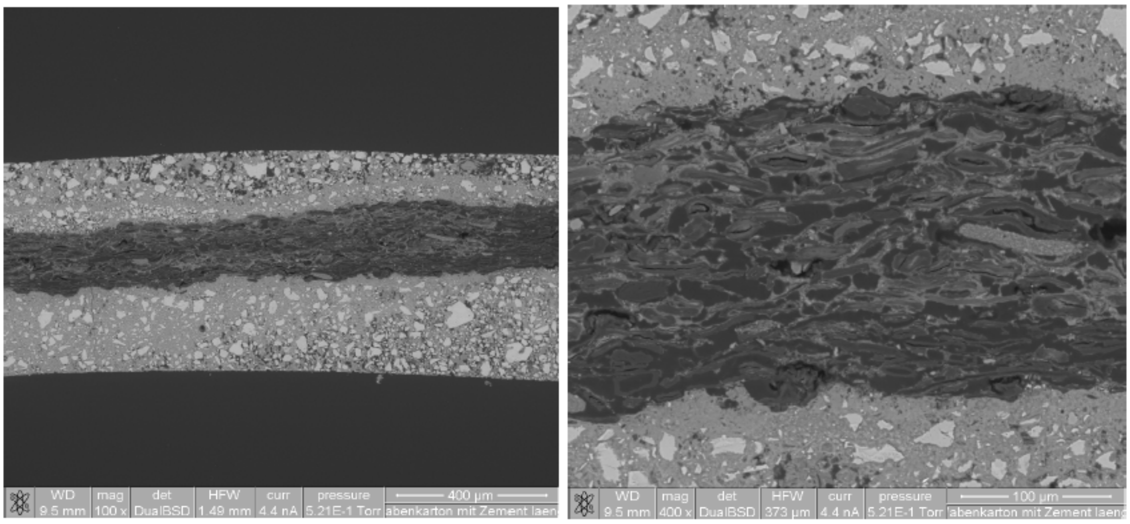


Fig. [VI / 10] - Microscopic image of a cement-impregnated paper section (100x magnification) (a). Microscopic image of the fibre network with hydrated cement filling the pores (400x magnification) (b). Reproduced with kind permission from G. Peschke, IfB, ETH Zurich [36]

In order to avoid creep strains in structural elements, in following lines the combination of pre-stressed paper and cement is analyzed.

6.3 **Pre-stressed paper + cement**

Paper and cement are two completely different materials, but make very interesting combination as a composite material. Paper products are very sensitive to humid environments, insects and fire, while cement has very good performance in these fields and complements paper perfectly Fig. [VI / 11].

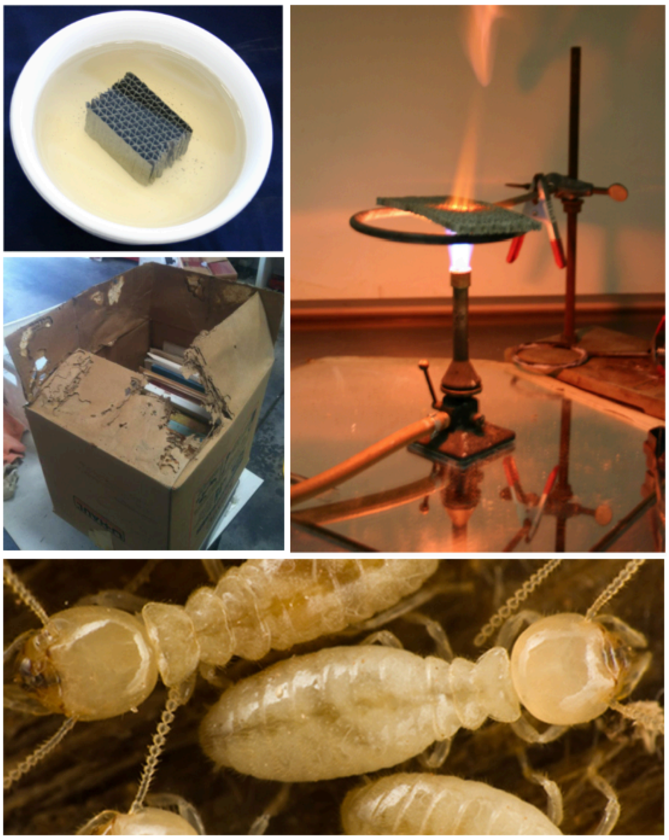


Fig. [VI / 11] - Paper-cement, as a composite material, has good performance towards humid ambients, insects and fire.

The mixture of these two materials not only enhances complementary protection between them, but mechanical properties as well. As one can see in figures [IV / 19, 20, 21], paper works much better in tension than in compression, because of buckling of its free fiber segments. Cement, on the other hand, does not work very well in tension. But, while humid, it is able to impregnate pores between fibers, confine the fiber segments and once solid, prevent their buckling. Besides, the proper cement has high compressive strength, so the composite material paper-cement would finally have extended compressive area, which could enter in balance with already important tension area Fig. [IV / 19].

6.3.1 Precautions

Introducing cement in contact with linerboard as a complementary material brings several possible drawbacks which should be prevented.

Cellulose fibers are hygroscopic, which means that they have ability to attract and hold water molecules from the surrounding environment. When humid cement and linerboard enter in contact, dry cellulose fibers will start to “steal” water from cement, which will produce cement dehydration and obstruct its correct setting.

On the other hand, linerboard should be under tension when entering in contact with humid cement. As seen in part 4.1.5, water acts as softener of paper, which means that while cement sets with lack of water “stolen” by cellulose fiber, linerboard would start to strain (or creep) additionally under the softening effect of “stolen” water.

Therefore, it is essential to waterproof intrinsically cellulose fibers before entering in contact with humid cement.

This fact is evidenced in Almut Pohl’s study:

“*When the honeycomb is immersed in the cement slurry, the paper material immediately soaks up water from the slurry, which causes it to swell. The paper sections that are not restrained by the adhesive form waves parallel to the corrugation axes, a phenomenon also referred to as ”cockling”. When the applied cementitious material dries, it ”freezes” the buckles, which prevent the cockled sections from bearing load. Figure 5.20 shows the buckles in the straight layer of a cement-impregnated paper honeycomb sample.*” [36]

Fig. [VI / 12] - Cockling in the cell walls of a cement-impregnated corrugated paper honeycomb sample. [36]

Another important aspect is the creep property of cement in relation to pre-stressed fiber network. Intervention strategy (6.2) contemplates theoretical way to capture elastic energy of pre-stressed linerboard and transmit it in form of compression to the capturing element, which is, in this case, perfectly elastic. If this capturing element is cement, than it is important to count on its retraction (shrinkage) property and creep strain under compression. If it shrinks more than linerboard, than there will be no medium to maintain the fiber network in tension. If the fiber network loses tension, then it returns to viscoelastic period.

Quantification of cement shrinkage can be seen in a study of Pavel Padevět and Petr Bittnar [34].

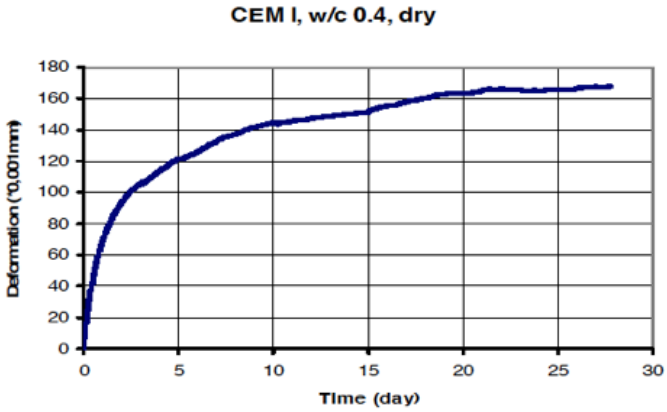


Fig. [VI / 13] - Result of measure the creep and shrinkage cement paste with w/c 0,4. [34]

The importance of obtaining highest elastic modulus with minimum weight is mentioned in Observation 7. Although cement would complement very well the paper products, its high specific weight would produce a notable increment of composite material paper-cement compared to specific weight of paper, which means that although improving compressive strength of paper, for equal elastic modulus, the tensional mechanical efficiency would lower.

Fig. [VI / 14] - Cement specific weight range. In dry powder stage it depends on compaction level. In wet stage, it is notably increased.

6.3.2 Preventions

The aim of this work is not the fundamental characterization of complete composite material (pre-stressed paper-cement), but the theoretical study of its microstructural mechanisms, indicating which direction interventions should take for an optimal microstrucural control over the material. Therefore, here are commented some possible preventions to count on, without thorough insight.

Before any contact between cement slurry and linerboard, the hygroscopic fiber network has to be waterproofed (6.3.1).

There are two principle approaches for waterproofing. First, the application of protective layer on the faces exposed to inclemencies, and second, the intrinsic waterproofing of fibers. The first approach completely closes access to the interior pores of fiber network, while the interior structure of fiber network remains intact. This option inhibits cement penetration into the pores, which makes impossible intervention strategy impregnation (6.2). In the Fig [VI / 15] one can see the section of external coating applied to the sheet of paper.

Fig. [VI / 15] - Cross-sectional image of a coated paper sheet. The thickness is of the order of 0,1 mm (KCL). [01]

The second waterproofing approach should impregnate the fibers without obstructing pores in the network. That could be done immersing linerboard in certain solution which would waterproof fibers when dried.

In University of Pretoria (unknown author), some experiments of impregnation of cardboard into Boric acid as fire retardant is done, but without microscopic analysis Fig [VI / 16].

Boric acid could be interesting solution to explore. As explained in their study, "*Boric acid is a salt of the Borax compound (also known as sodium borate, sodium tetraborate / disodium tetraborate). it is water soluble white powder consisting of soft colorless crystals. Boric acid is used in a variety of applications such as weatherproofing and fireproofing fabrics, ointments, eye drops, soaps, as a preservative, in the manufacture of cements, glass, leather and artificial gems, as an insecticide for cockroaches and carpet beetles, and in fungus control for citrus fruits. The Smart Living Handbook suggests soaking cardboard in a solution of boron as a low cost fire retardant before installing it as insulation.*" As it is used for weatherproofing, maybe it could protect well enough the fibers against water absorption.

Another solution to explore could be a very liquid mixture of starch glue with high proportion of water. Whichever solution used to explore, it should be very liquid (needs to soak every fibre), and should not be brittle. After soaking in solution, linerboard should be put under tension, which means that all its fibers would be strained. If waterproof is brittle, it would crack and open contact between fibre and water contained in cement. Starch glue is flexible after drying, so it could strain without cracking.

Fig. [VI / 16] - Boric acid treated cardboard being tested to see how quickly it catches fire / singes. [University of Pretoria]

Regarding to precaution of shrinking and creep property of cement, in Fig. [VI / 17] are represented graphically strains which should be controlled over time. On one hand, shrinking and creep strain of cement under compression would have a negative direction. On the other, tension in linerboard would produce a creep strain in positive direction. In order to obtain pre-stressed paper-cement as explained in Fig. [VI / 7], the elastic strain of linerboard must measure at least as a sum of creep strain of cement and linerboard. In contrary, it cannot be assured that all fiber segments would be activated, which means that final paper-cement product would still be in a viscoelastic period. Quantification of these strains require special attention and thorough insight which overflows aims of this research.

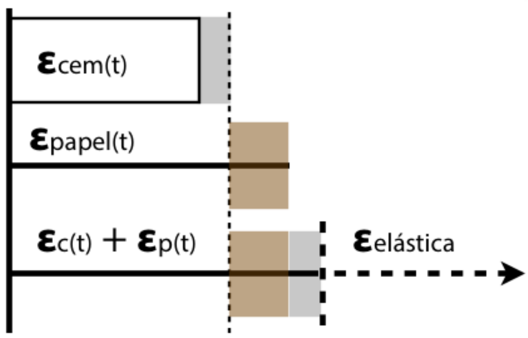


Fig. [VI / 17] - Graphical representation of strains. To obtain long-term pre-stressed paper-cement, the elastic strain of linerboard must measure at least as the sum of creep strains of cement and linerboard. Elaborated by the author.

An important inconvenience that cement brings to paper-cement as composite material, is its specific weight, which in wet state is more than four times greater than the specific weight of the linerboard Fig. [VI / 14]. Cellulose fiber network has a great proportion of pores Fig. [VI / 18], which would occupy cement slurry. In order to reduce specific weight of paper-cement, the quantity of cement inside the pores should be controlled.

One of the possibilities which would not obstruct cement penetration into the pores could be occluded air in the cement slurry. This would bring a "sponge" effect and would reduce notably the final specific weight of paper-cement. Higher the cement strength, less cement is needed and lighter will be the final material. Therefore, high strength cement slurry with occluded air should be used in combination with pre-stressed linerboard to obtain optimal mechanical efficiency of paper-cement.

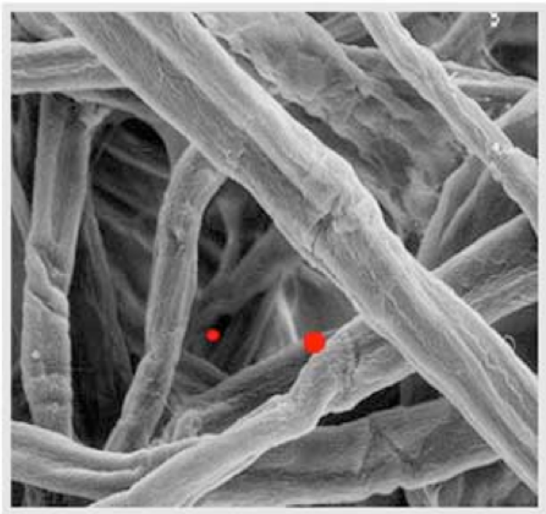


Fig. [VI / 18] - SEM image of cellulose fiber network.

7. Expected mechanical properties

7.1 Paper-cement in relation 1:1

As mentioned in previous chapter, high specific weight of cement would have negative influence on paper-cement mechanical efficiency. In Fig. [VII / 1] Kraft paper, cellulose fiber and paper-cement are compared in hypothetic case where cement slurry occupies completely all the pores inside cellulose fiber network.

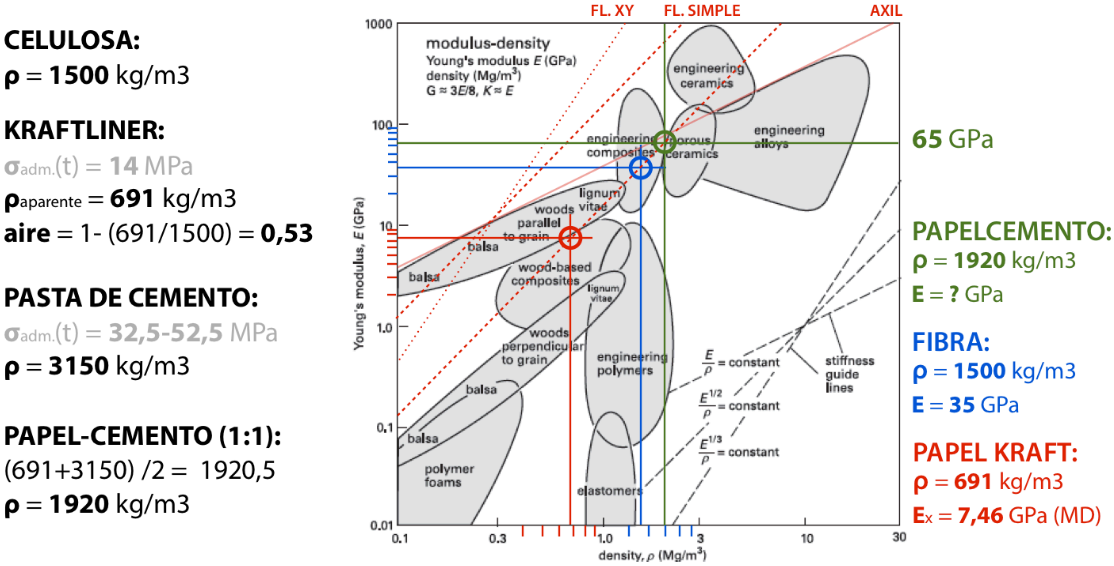


Fig. [VII / 1] - Comparison of mechanical efficiency between Kraft paper, cellulose fiber and paper-cement. Edited by the author.

Knowing the specific weight of the cellulose (1500 kg/m^3) and linerboard (691 kg/m^3), one can determine the volume which air occupies inside the cellulose fibre network (53%) Fig. [VII / 1]. Rounding, if cement occupies these 50% instead of air, the final specific weight of paper cement would be ρ = 1920 Kg/m^3. In the same figure, the green vertical line on the graphic represents the density of paper-cement. In order to maintain the same efficiency in pure bending that kraft paper and the cellulose have, it would be necessary to obtain elastic modulus of 65 GPa for paper-cement.

From Summary on chapter 5, one can see that maximum elastic modulus for linerboard can arrive up to 12 GPa, which means that it is necessary to find a mechanism for increasing this elastic modulus. So, if cement occupies all the pores inside the fiber network of linerboard, obtained paper-cement needs around 5 times higher elastic modulus than maximum one linerboard can have.

The high slope of the pure bending line from the diagram above demonstrates how sensible is the mechanical efficiency to the specific weight of materials. Therefore, it is in highest interest for mechanical efficiency to reduce the quantity of cement slurry.

7.2 Paper-cement with high strength cement and occluded air

As observed in Summary on chapter 5, linerboard should not be exposed to tension higher than 14 MPa for long-term behavior. In Fig. [VI / 7], 14 MPa is established as a long-term pre-stressing tension of linerboard. It means that, if no creep strain occurs in linerboard before transmitting this tension to the cement in form of compression, the maximum compression that cement would have to support is 14 MPa.

For more accurate approach, not only specific weights should be taken into account, but also the strength comparison between paper and cement. If the admissible strength of paper is 14 MPa, and we use cement which can support 52,5 MPa, the strength relation between them for a volumetric proportion paper:cement=1:1 is 3,75 (Fig. [VII / 2]). It means that if cement 52,5 occupies all the pores inside the fiber network, it will be able to support 3,75 times compression than linerboard is able to provoke. That indicates that cement strength capacity would not be maximally used, and the cement-paper would carry unnecessary weight. The strength relation would be paper:cement = 1:3,75.

Therefore, for optimal paper:cement relation, if cement 52,5 is used, the volumetric relation cement slurry:occluded air should be 1:3,75, which would result in a specific weight of cement 840 Kg/m^3 (3150 Kg/m^3 / 3,75). Paper-cement composed of this type of cement and pre-stressed intrinsically waterproofed linerboard, would have properties as described in following text and Fig. [VII / 2].

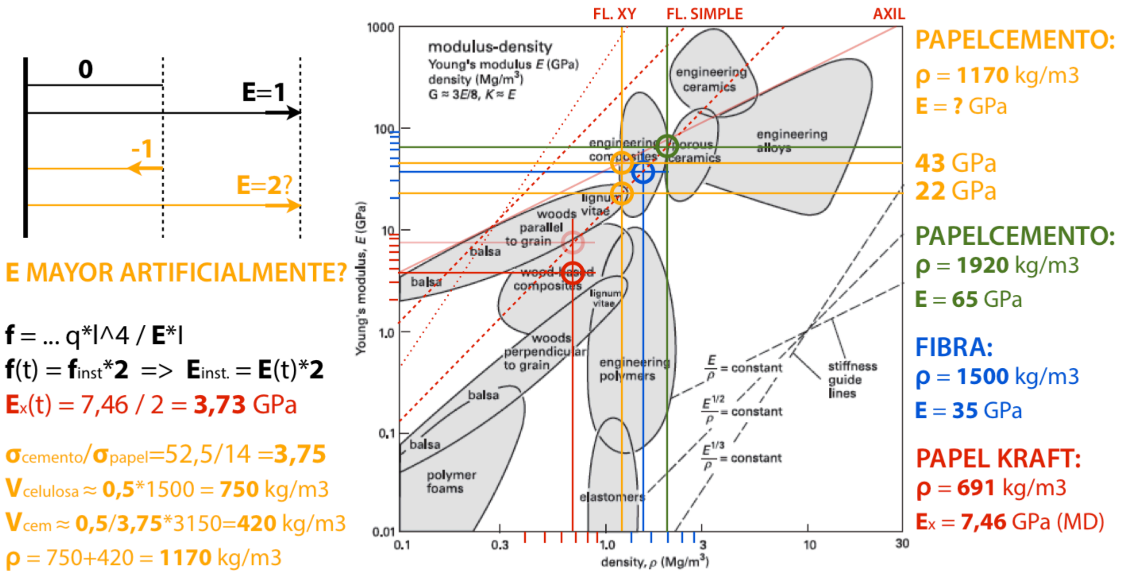


Fig. [VII / 2] - Comparison of mechanical efficiency between Kraft paper, cellulose fiber and paper-cement with high strength cement and occluded air. Edited by the author.

Vertical orange line represents the weight of paper-cement 52,5 with occluded air. Repeating the mechanical efficiency comparison from Fig. [VII / 1], to maintain efficiency in pure bending (fl. simple) as the hypothetic solid cellulose paper (blue) has, it would be necessary to obtain elastic modulus of 22 GPa. And for pure axil tension efficiency, 43 GPa would be necessary.

If elastic modulus is described as "*(...) the value of necessary tension to double the length of a bar (...)*" [36], then the expected elastic modulus of pre-stressed paper-cement could be explained this way...

To double the length of a bar which has the initial tension equal to zero (Fig. [VII / 2]) we need certain amount of force which would produce tension expressed as E=1. If the same bar is initially compressed, it would have a tensional state equal to -1. Now, in order to double its length, the amount of force to apply would be the sum of two forces. The first one is the force necessary to decompress the bar, and the second one is the force which would double its length. The final tension in the bar in both cases is equal, but for a pre-stressed bar it is necessary to apply much more force to double its length. Then, it can be said that its elastic modulus is "artificially" increased. For quantification of this "artificial" increase, the most precise result would bring the load test.

What we can obtain by pre-stressing paper-cement is the "artificial" control over its elastic modulus. It is very important factor if we pay attention to the influence it has in the mechanical efficiency of materials. For instance, if we analyze the kraft paper efficiency for a long-term behavior, the situation would be as follows...

When we calculate deflection of a beam, elastic modulus has linear influence ($\delta=...q*l^4/E*J$) on a final result Fig. [VII / 2]. In viscoelastic materials, total deflection is a sum of elastic deflection and creep deflection. If we imagine that for same elastic modulus, after certain time, deflection doubles, when we eliminate factor time, we could calculate it as if it was elastic material, but with elastic modulus two times smaller. The same result would be obtained.

In Fig. [VII / 1], red circle represents instant “elastic” mechanical efficiency of linerboard for E=7,46 GPa. If factor time is introduced, then the red circle would be situated as presented in Fig. [VII / 2]. If creep strain equals elastic strain, it is like representing linerboard as elastic material with E=3,73 GPa.

This is the reason why it is important to pre-stress paper-cement. This mechanism for “artificial” control of elastic modulus is the most effective way to convert paper product (cardboard) into “structural cardboard”, efficient enough to compete with other materials.

7.3 **Potential for structural uses and economic estimation of pre-stressed paper-cement**

Linerboard is a very thin surface material. This property can be used for production of pre-stressed planar layered elements with very accurate thickness. If used only one layer, paper-cement would be obtained. Various simultaneous layers could form a cardboard-cement, and even beams or prefabricated slabs.

Intentional controlling of tensions in linerboards, during the pre-stressing process, would enable zoning of stresses inside the final structural element. Whole section could be uniformly pre-stressed if the element is to support pure axial tension, or partially stressed if it is to support flexion. On the other hand, pre-stressed cardboard-cement boards, can be used for assembling of structural elements with accurate control of pre-stressed zones to support tensions Fig. [VII / 3]. These mechanisms would increase the efficiency of paper-based structural elements.

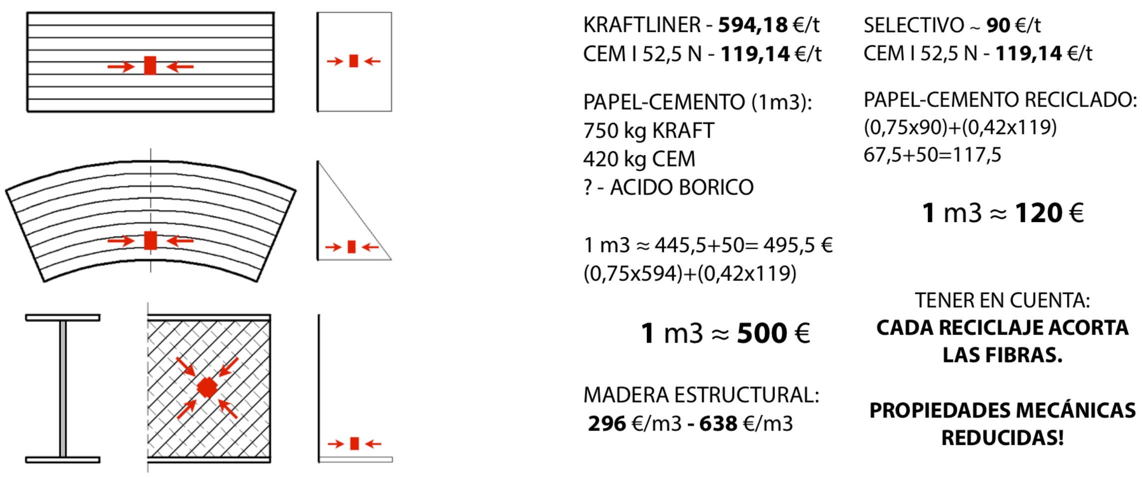


Fig. [VII / 3] - (a) Graphic representation of potential uses of structural cardboard. (b) Rough economic estimation of paper-cement with new linerboard (virgin fibers) and linerboard made of recycled cardboard (recycled fibers). Elaborated by the author.

Regarding to costs[2] [51], linerboard made of virgin fibers is not very cheap material (594,18 €/t), so the price of material for paper-cement production would be around 500 €/m^3 Fig. [VII / 3]. Compared to structural wood, it is in the higher price range. If recycled fibers are used for production of linerboard, its price is much lower (around 90 €/t), which gives very competitive price for paper-cement of 120 €/m^3. However, it is important to pay attention on origin of fibers, because every recycling process shortens fibers, which leads to reduced mechanical properties of linerboard. The most accurate information about mechanical properties would be the load test comparison of paper-cement made of virgin and recycled linerboard.

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[2] Values for price estimation date May 2013 for European market.

8. Conclusions and recommendations

8.1 **Conclusions**

The objective of this research was to evaluate if cardboard could and should be used as a durable load-bearing element in architecture. Its properties are well known and studied in paper and packaging industry, which brings a solid background for its analysis from architectural point of view. Although cardboard is widely used in architecture (as furniture, insulation, filling, etc.), studied and tested as a structure, it found difficulties to persist as a durable architectural structure. The focus in this research was to understand the reasons of these facts and to search for adequate improvements in cardboard production and treatment, which would lead to its optimal properties for use as a long-term structure in architecture.

Cellulose fibers, which are the main constituent of paper products, are extracted from wood. As such, it is logical to expect properties of cardboard to be similar to the properties of wood. The main difference between cardboard and wood is in their microstructure. In wood, cellulose fibers are in parallel disposition inside the lignin matrix, while in cardboard, the microstructure is in form of a random network of cellulose fibers bonded between them in drying process. Cellulose fiber is the strongest constituent in wood, but it is hygroscopic. On the other hand, lignin has poor mechanical properties, but it acts as waterproofing constituent. As cardboard is made of pure fibers, it is much more sensible to exterior conditions and humid ambients than wood. This leads to the first important factor for using cardboard as structure, which is waterproofing. In absence of lignin, some other substance should be applied, which would protect intrinsically all the fibers. Some ideas are given in part 6.3.2.

The network of fibers in cardboard is formed under the influence of papermaking process with mayor orientation of fibers in machine direction, but still, with many fibers randomly oriented. During the drying process the network is under certain tension in order to avoid irregularities in surface of paper, which shrinking could provoke. These facts produce two effects. First, fibers cannot work altogether in pure axial direction, and second, in unstressed cardboard element, some fibers are under tension, while others remain inactive. The sum of these effects is responsible for creep and relaxation phenomena in cardboard, which notably reduce mechanical efficiency of paper products (see Chapter 5). This leads to the second important factor, which is the need to tension paper products before their usage as structural elements, in order to activate all fibers inside the network and avoid creep strains of structural elements.

To waterproof and activate all fibers, certain intervention strategy is necessary (see 6.2). In this study, it is opted to analyze a mixture with cement, as a substance able to penetrate inside the pores between fiber network segments, providing improvement in compressive behavior, fireproofing and protection against insects (see 6.3).

The complex microstructure and influence in production process of cardboard make difficult to obtain accurate information and prediction of its behavior as durable load-bearing element. In fact, there are many attempts nowadays which, assembling beams out of existing cardboard products and putting them to load tests, try to deduce cardboard properties and its behavior. That, indeed, is necessary and is the most accurate way to obtain this information. However, using existing cardboard products to assemble elements for structural use in architecture will always result in structures with viscoelastic behavior, high strains and lower mechanical efficiency than the one of wood products. It is doubtable even that long-term cardboard structure would be able to compete economically with wooden structure. The only reasonable sense for using existing cardboard products as structure is recycling and reutilization, which are strong ecological arguments, but with weak structural efficiency.

Structural cardboard, or the combination of waterproofed pre-stressed paper product and high-strength cement with occluded air, is the sequence of necessary interventions to implement, in order to synthesize ecological arguments, mechanical efficiency and economic competitiveness.

Fig. [VIII / 1] represents the summary of this research in numbers. Mechanical properties of cardboard which adopted my colleague Maria Isabel Umbert [36] in her study, are compared with probable mechanical properties of cardboard deduced from this research and with expected mechanical properties of structural cardboard. Red numbers represent decrease in properties, while green numbers represent improvement.

The most important factors which structural cardboard would provide are:

1. Elastic behavior (absence of viscoelastic effects)

2. Artificial control of elastic modulus (with pre-stressing)

3. Assembling of structural elements with intentional pre-stressed zones (in tension).

Two mayor inconveniences of structural cardboard are its specific weight increase respect to cardboard (1200 kg/m^3 vs 691 kg/m^3), however, obtained mechanic efficiency would be much higher in structural cardboard than in ordinary one. The other one is that structural cardboard is not as easy to recycle as cardboard.

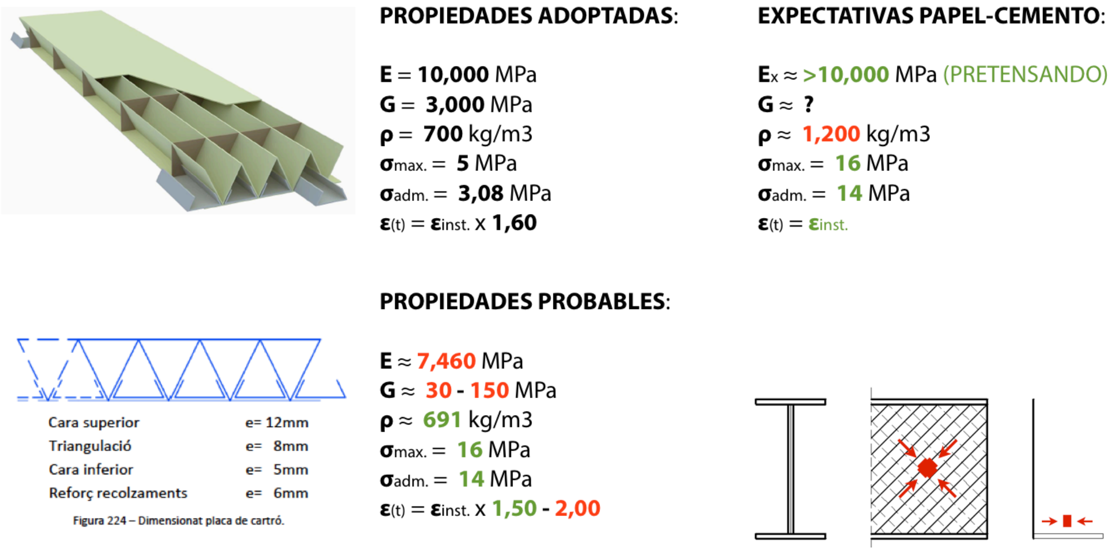

Fig. [VIII / 1] - Comparison of mechanical properties of cardboard adopted by Maria Isabel Umbert [45] for her design of prefabricated cardboard slab, probable mechanical properties that cardboard would have and expected properties of structural cardboard. Elaborated by the author.

8.2 **Recommendations for future investigations**

This research was aimed to give a background to architects for future researches and experiments. Before starting to assemble structural profiles with ordinary cardboard, which from point of view of mechanical efficiency does not have much sense, it is recommendable to establish first an intervention strategy for improvement of mechanical efficiency. In this research, cement was selected as a complementary material to cellulose fiber network, which opens some fields to experiment.

The first important field is an intrinsic waterproofing of cardboard without obstructing the pores, which is a necessary step before entering in contact with cement slurry or other humid ambients.

The second field is the production of pre-stressed structural cardboard in order to assemble profiles with intentional pre-stressed zones.

The third field to study is the production of extruded cardboard profiles aimed to be pre-stressed and impregnated.

As a complementary material cement is not a must. It is just author’s choice in this work. What is important is to bring cardboard in its elastic phase before using it as long-term structure. Viscoelastic behavior reduces notably its efficiency.

Computer modeling can be helpful for intuition of structural behavior of elements, but the random orientation of fibers in fiber network imposes that only reliable data of mechanical properties has to be deduced from load tests.

9. References

[01] **ALAVA,** M. 1, **NISKANEN,** K. 2. **The physics of paper.** 1 Helsinki University of Technology, Laboratory of Physics, PO Box 1100, 02015 HUT, Finland, 2 KCL Science and Consulting, PO Box 70, 02150 Espoo, Finland, Institute of Physics Publishing Reports on Progress in Physics, Rep. Prog. Phys. 69 (2006) 669–723 doi:10.1088/0034-4885/69/3/R03, **2006**.

[02] **ALLAOUI** S., **ABOURA** Z., **BENZEGGAGH** M.L. **Phenomena governing uni-axial tensile behaviour of paperboard and corrugated cardboard**. hal-00636962, Version 1-14 Jan **2013**.

[03] **ABOURA** Z., **ALLAOUI** S., **TALBI** N., **BENZEGGAGH** M.L. **Elastic behavior of corrugated cardboard: Experiments and Modeling**. hal-00636959, Version 1-14 Jan **2013**.

[04] **ALLAOUI** S., **ABOURA** Z., **BENZEGGAGH** M.L. **Study of the hygro-mechanical behavior of corrugated cardboard**. hal-00634671, Version 1-14 Oct **2011**.

[05] **ASHBY**, M. F. **Materials Selection in Mechanical Design** (Oxford: Butterworth-Heinemann). **1999**.

[06] **AYAN**, Özlem. **Cardboard in architectural technology and structural engineering: A conceptual approach to cardboard buildings in architecture.** Doctoral Thesis, ETH ZURICH, **2009**.

[07] **BAIG,** M.A., **WHITE,** W.O. **Multiple layer gypsum cellulose fiber composite board and the method for the manufacture thereof**. Patented, US. **2008.**

[08] **BALDWIN,** J. **Bucky Works: Buckminister Fuller's Ideas for Today**. Wiley & Sons, Inc. Publ. 26-127, USA. **1996.**

[09] **BAUM**, G.A., **BRENNAN**, D.C., **HABERGER**, C.C. **Orthotropic elastic constants of paper**. TAPPI J, pp. 64, 97-101. **1981**.

[10] **BANDYOPADHYAY**, A., **RADHAKRISHNAN**, H., **RAMARAO**, B. V., **CHATTERJEE**, S.G. **Moisture sorption response of paper subjected to ramp humidity changes: Modeling and Experiments**. Ind. and Engng. Chem. Res., vol 39, pp. 219-226, **2000**.

[11] **BERGLUND**, L. A., **PEIJS**, T. **Cellulose biocomposites – from bulk moldings to nanostructured systems**. MRS Bulletin 35, 201–207. **2010**.

[12] **BRUFAU I NIUBÓ**, Robert, **BLASCO I CASANOVAS**, Joan Ramón. **Resistència de materials**, **Modul 2**. Escola Tècnica Superior d'Arquitectura del Vallés, UPC, **2008-2009**.

[13] **CRIPPS,** A**. Cardboard as a construction material: a case study**. Building Research & Information 32, no. 3: 207-219. **2004.**

[14] **DUNN**, H. M. **Micromechanics of paperboard deformation**. Master thesis, Massachusetts institute of technology, Cambridge, Mass., USA, **2000**.

[15] **EEKHOUT** Mick, **VERHEIJEN** Fonsand, **VISSER** Ronald. **Cardboard in Architecture**. ISBN 9781586038205. Amsterdam: IOS Press, **2008**.

[16] **EMMERICH,** D.G. **Maisons en Carton**. Paris. **1983.**

[17] **GIBSON**, Lorna J. **The hierarchical structure and mechanics of plant materials**. Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA, **2012**.

[18] **GIRLANDA**, O., **FELLERS**, C. **Evaluation of the tensile stress-strain properties in the thickness direction of paper materials**. Nord. Pulp Paper Res. J., vol 22(1), pp. 49-56, **2007**.

[19] **GOSPODINOV**, Delyan, **STEFANOV**, Stefan, **HADJIISKI**, Vilhelm. **Use of the finite element method in studying the influence of different layers on mechanical characteristics of corrugates paperboard**. UDC/UDK 676.274.017:519.6. **2011**. ISSN 1330-3651.

[20] **HALONEN**, Helena. **Structural changes during cellulose composite processing**. Doctoral Thesis. Royal Institute of Technology, School of Chemical Science and Engineering, Department of Fibre and Polymer Technology. SE-100 44. Stockholm, Sweden, **2012**.

[21] **HUANG**, Hui. **Numerical and Experimental Investigation of Paperboard Creasing and Folding**. Licentiate Thesis No. 111, KTH School of Engineering Science Department of Solid Mechanics, BiMaC Innovation, Royal Institute of Technology, SE-100 44 Stockholm Sweden, **2011**.

[22] **ISO 1924-3:2005 (E). Paper and board - Determination of tensile properties - Part 3: Constant rate of elongation method (100 mm/min), 2005.**

[23] **ISO 9895 : 1989 (E)**. **Paper and board - Compressive strength - Short span test,1989**.

[24] **JODIDIO**, Philip. **Shigeru Ban: Complete Works 1985-2010**. Taschen, 2010. ISBN 9783836517003.

[25] **MANN**, R. W. **Determination of all nine orthotropic elastic constants for machine-made paper**. TAPPI Press, vol. 63, no. 2, pp. 163 - 166, **1980**. ISSN 0039-8241.

[26] **McDONALD,** D. B. **Gypsum Wood Fiber Structural Insulated Panel Arrangement**. U.S. Patent 20080245007. **2009.**

[27] **McQUAID,** M. **Shigeru Ban**. Phaidon, London. **2004.**

[28] **MERKLEY,** D., **LUO,** J. C. **Fiber cement composite materials using cellulose fibers loaded with inorganic and/or organic substances**. United States Patent 6872246. **2004.**

[29] **MIHASHI**, H., **KIRIKOSHI**, K., **ARIKAWA**, S. **Recycling of Used Paper as a Building Material**. Proceedings of the International Rilem Workshop, Disposal and Recycling of Organic and Polymeric Construction Materials, Koriyama Japan, **1995**.

[30] **MOHR**, J. Benjamin. **Durability of pulp fiber-cement composites.** Dissertation, Georgia Institute of Technology, **2005**.

[31] **NISKANEN**, Kaarlo (Edited by). **Mechanics of Paper Products**. ISBN 978-3-11-025461-7, FSCN, Mid Sweden University SE-851 70 Sundsvall, Sweden, **2012**.

[32] **NYGARDS**, M., **FELLERS**, C., **OSTLUND**, S. **Measuring the stress-strain properties of paperboard**. Pulp Paper Sci. J., vol 33(2), pp 1-5, **2007.**

[33] **NYGARDS**, M., **JUST**, M., **TRYDING**, J. **Experimental and numerical studies of creasing of paperboard**. Int. J. Solids Struct., vol 46, pp. 2493-2505, **2009**.

[34] **PADEVĚT**, Pavel, **BITTNAR**, Petr. **Measuring the creep of cement paste specimens.** Department of Mechanics, Czech Technical University in Prague. **2009**.

[35] **PERSSON**, Kent. **Micromechanical modelling of wood and fibre properties.** Doctoral Thesis, Lund University, Department of Mechanics and Materials, Sweden, **2000**. ISRN LUTVDG/TVSM--00/1013-SE (1-223) ISBN 91-7874-094-0 ISSN 0281-6679

[36] **POHL**, Almut. **Strengthened corrugated paper honeycomb for application in structural elements**. Institute of Structural Engineering Swiss Federal Institute of Technology, Zurich, **2009**.

[37] **RAMARAO**, B.V., **CHATTERJEE**, S.G. **Moisture Sorption by Paper Materials Under Varying Humidity Conditions**. The Fundamentals of Papermaking Materials (edited by C.F. Baker), Pira International, UK, vol 2, pp. 703-749, **1997.**

[38] **RAMASWAMY,** Shiri, University of Minnesota, **RAMARAO,** B.V., State University of New York. **3-D Characterization of the Structure of Paper and Paperboard and Their Application to Optimize Drying and Water Removal Processes and End-Use Applications**. (DOE Project DE FC07-00ID13873). A Final Report to the U.S. Department of Energy August 29, **2004**.

[39] **SCHÖNWÄLDER**, Julia. **Mechanical properties of Cardboard**. Phd. TUDelft, **2008**.

[40] **SCHÖNWÄLDER** Julia 1, **Van ZIJL** Gideon 1,2, **ROTS** Jan G. 1. **A computational model for cardboard creep fracture.** 1 Delft University of Technology, 2 University of Stellenbosch Faculty of Architecture, Berlageweg 1, 2628 CR Delft, The Netherlands, **2006**.

[41] **SCOTT**, W. E., **ABBOTT**, J. C., **TROSSET**, S. **Properties of Paper: An Introduction**. TAPPI Press, Atlanta, Georgia, 2nd ed., revised ed., **1995**.

[42] **SEHAQUI**, H., **ZHOU**, Q., **BERGLUND**, L. A. **Soft Matter**. 7, 7342–7350. **2011**.

[43] **SOYKEABKAEW**, Nattakan. **All-Cellulose Composites**. Doctoral Thesis. Department of Materials Queen Mary, University of London Mile End Road, London, E1 4NS. **2007**.

[44] **STARK**, N. M., **ROWLANDS**, R. E. **Effects of wood fiber characteristics on mechanical properties of wood/polypropylene composites**. Wood & Fib. Sci. 35, 167–174. **2003**.

[45] **UMBERT FEBRER**, Maria Isabel. **Disseny i anàlisi d'un element prefabricat de cartró reciclat que treballa a flexió**. Viabilitat del cartró com a material de construcció. UPC, **2012**.

[46] **VAN ZIJL**, G.P.A.G., **DE BORST**, R., **ROTS**, **J.G.**, Borst. **A numerical model for time-dependent cracking of cementitious materials**. International Journal for Numerical Methods in Engineering, vol 52, pp. 637-654, **2001**.

[47] **VEHNIÄINEN**, Annikki. **Single fiber properties - a key to the characteristic defibration patterns from wood to paper fibers**. Dissertation, Helsinki University of Technology, Department of forest Products Technology, **2008**. ISSN 1457-6252

[48] **WEGST**, U.G.K., **ASHBY**, M. F. **The mechanical efficiency of natural materials**. Phil. Mag. 84, 2167–2181. **2004**.

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[49] **www.aspapel.es**
ASPAPEL, Asociación Española de Fabricantes de Pasta, Papel y Cartón.

[50] **www.fefco.org/index.php?id=172**
1- FEFCO Organization Official Website, June 2006: "**Lifecycle Analysis - Assessment**"
2- FEFCO Organization Official Website, 2003, Issue 3: "**European Database for Corrugated Board: Lifecycle studies**", FEFCO-Groupement Ondulé-ECO

[51] **www.foex.fi**
Provider of audited, trade-mark registered pulp, paper, recovered paper and wood based bioenergy / biomass price indices.

[52] **www.ipst.gatech.edu**
Institute of paper science and technology.

[53] **www.iso.org**
International Organization for Standardization, 2003. "**ISO 14040-14044:1997**; **Environmental Management - lifecycle Assessment - Principles and Framework**"

[54] **www.paperindex.com**
B2B marketplace for online trading of pulp, paper and related products.

[55] **www.paperonweb.com**
The ultimate resource for the pulp and paper professional.

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